Fishes, Invertebrates and Marine Pla[illegible]

The Beaufort Sea and the Search for Oil

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Beaufort Sea

The Beaufort Sea
and the Search for Oil

Fishes, Invertebrates and Marine Plants

by
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Chrysophyta *Diploneis* (marine diatom magnification x252) from seawater sample from below ice in Balaena Bay, N.W.T., June 1975.

PHOTO BY: BILL ADAMS

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Foreword

As land sources of petroleum are being depleted, attention is being focused on offshore sedimentary formations. This is particularly true in North America and, in Canada, almost the whole of the continental shelf of the Beaufort Sea has been subject to permits by oil companies for a number of years. Seismic and other geophysical surveys have been carried out over the whole region. Until the summer of 1976, the only drilling which had taken place offshore in the Beaufort had been from artificial islands constructed in shallow water close to the Mackenzie Delta. In 1976 Canadian Marine Drilling Limited, a wholly-owned subsidiary of Dome Petroleum, obtained drilling permits for two wildcat wells in the southern Beaufort Sea. The expansion of exploratory drilling — perhaps followed by the drilling of production and transport by pipelines and tankers — will have environmental and social implications which will have to be dealt with.

Of immediate concern is how the Beaufort Sea region might be degraded. The major immediate threat is an undersea oilwell blowout during the exploratory drilling phase. Questions such as: What are the probable consequences of an oilwell blowout? And: What is the capability to control a blowout and to clean up the oil? . . . prompted the federal government to postpone the granting of Drilling Authorities until the results of the regional environmental assessment could be known.

Cabinet, in July 1973, granted Approval-in-Principle for exploratory drilling and, that the Authority would be issued conditional on constraints which would be determined by the Beaufort Sea Project. (This name was given to the group of studies from which the assessment would be made.)

An unusual feature of the Project was its joint government and petroleum industry nature. Industry initially contributed $4.1 million and by the time the Project was completed in late 1976, the total cost was an estimated $12 million. Included in the Project were studies on Wildlife, Marine Life, Oceanography, Meteorology, Sea Ice and Oilspill Countermeasures. These provided ecological baselines, a better understanding of the physical environment, knowledge related to the consequences of a possible oilspill, and methods of oil cleanup in ice-infested waters. Reports on these studies were published as The Beaufort Sea Project Technical Report series. They were written for a specialized audience of consultant engineers, industry and government officials. Part of the information contained in the Technical Report series has been synthesized in this book, and in the other four volumes of the Beaufort Sea Project Overview Report series:

Birds and Marine Mammals
Oil Spill Countermeasures
Crude Oil in Cold Water
Oil, Ice and Climate Change

In terms of bulk acquisition of new information over a short time-period, the Project was unique, at least in comparison to the decades of previous investigations in the Beaufort Sea. Bottom trawling from a large oceanographic vessel had not been attempted before on the Mackenzie Shelf. More sampling was conducted farther offshore using several techniques many times over. In fact, for fish studies alone, the Project biologists made almost 300 collections using nets and trawls in eight independent studies; this compared to about 450 collections of 17 studies during the preceding 20 years.

However, the reader should be aware that since the Project's completion more information has been gathered by government and industry biologists. Nevertheless, this Overview Report remains a helpful introduction to a complex and ever-changing topic.

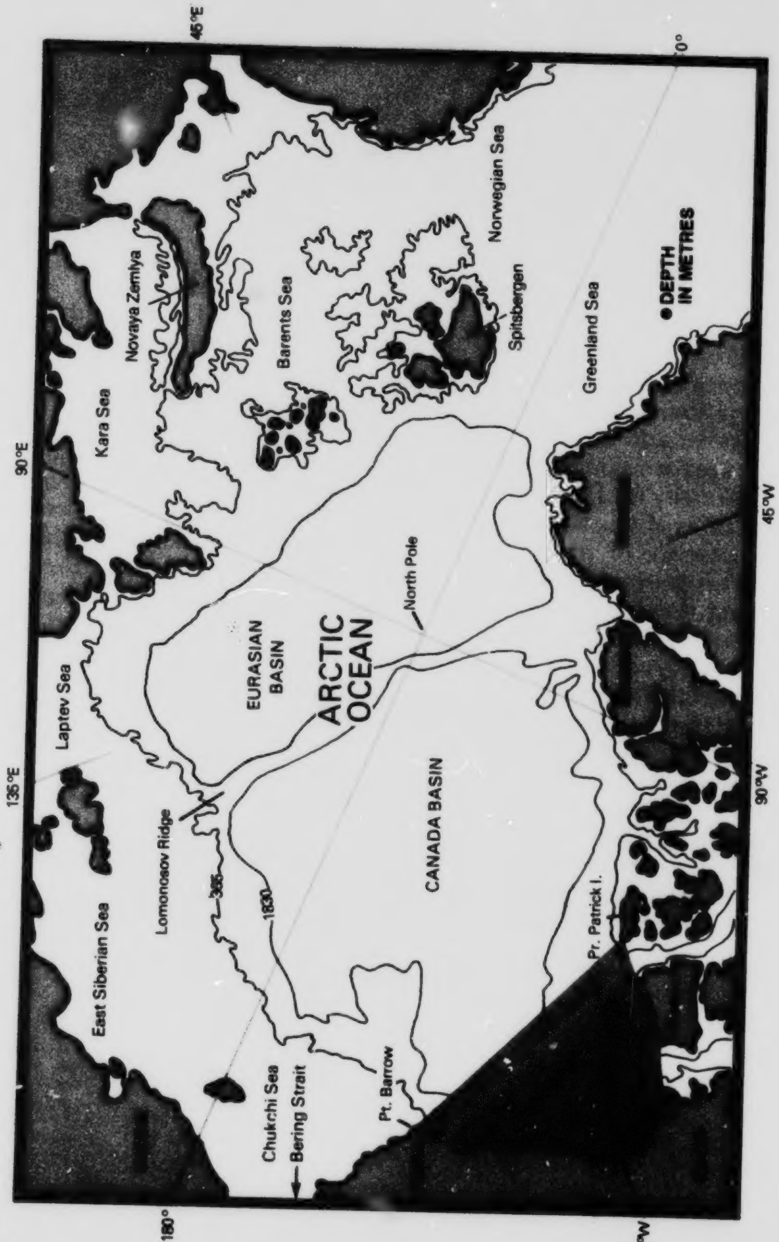
Acknowledgements

We are indebted to the scientists and technicians of Fisheries and Oceans Canada, Environment Canada and several private firms whose research was the basis for this report. Their names, too numerous to mention here, are listed in Appendix B. In addition to their Beaufort Sea Project Technical Reports, these biologists, chemists, physicists and engineers provided other background material and advice. Special thanks to Allen R. Milne, manager of the Beaufort Sea Project, who envisioned the Overview series, of which this is the final book. Larry de March, Bill Bond, and Ken Chang Kue, of the Freshwater Institute, and E.H. Grainger, of the Arctic Biological Station, reviewed the manuscript. Funding for publication was provided through the Northern Oil and Gas Action Plan of the federal government.

Introduction

This is the final volume of the Beaufort Sea Project series of Overview Reports. Its theme is a general outline of life histories and behavior of Beaufort Sea region fishes, marine invertebrates and plant life, and their relationship with each other and their surroundings. It explains the dependence of these life forms on the Mackenzie River, estuary and Arctic Ocean, the necessity for flexible "life-styles" forced on them by fluctuating conditions of salinity, temperature, ice, the availability of prey and the presence of predators (including Man). The format of this report is geographical: beginning with the Mackenzie River, then moving downstream to the estuary, and into the Beaufort Sea. Because of this river/estuary/ocean format, the reader will find a certain degree of overlap in content. The intention is to accentuate the variability and extremes of the fish-invertebrate-plant environments, especially for fish that travel and migrate.

The report then introduces Industrial Man to the scene, primarily the people involved in the exploration for gas and oil reserves. Use of the fish resource by native fishermen is discussed, as are the socio-economic effects of the oil industry presence. The dangers and effects of possible oil spills on the various life forms are outlined in the concluding sections of the report.


45°E
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90°E
45°W
135°E
90°W
180°
135°W
Kara Sea
Novaya Zemlya
Barents Sea
Norwegian Sea
Spitsbergen
Greenland Sea
DEPTH IN METRES
Laptev Sea
EURASIAN BASIN
ARCTIC OCEAN
North Pole
East Siberian Sea
Lomonosov Ridge
365
1830
CANADA BASIN
Pt. Patrick I.
Chukchi Sea
Bering Strait
Pt. Barrow

Figure 1: North Polar Region.

Historical

The Beaufort Sea is a wedge-shaped expanse of the Arctic Ocean bordering the northern coasts of Alaska and north-western Canada. Cartographers define it as that portion of the Arctic Ocean that lies south and east of a line connecting Point Barrow, Alaska, and Lands End on Prince Patrick Island in the Northwest Territories. To the west lies the Chukchi Sea; to the east Amundsen Gulf, Banks Island and M'Clure Strait; to the north — 3 500 metres/12,000 feet below the water — lies the Canada Abyssal Plain (Figure 1). This 500 000 square-km (200,000 sq mi) body of water was named for Sir Francis Beaufort, a British naval officer and hydrographer who, by 1859, had explored and roughly charted much of this rugged coastline. The place names of the region today are a reminder of many early explorers and their quest for the Northwest Passage.

The search for a direct sea route from western Europe to the Orient began much earlier with Martin Frobisher in 1576. Successive voyages, financed by mercantile interests, failed to find a northern route to the Pacific Ocean but did result in the granting of a charter in 1670 to the Hudson's Bay Company "to trade into Hudson's Bay." In the first half of the 18th century the British Admiralty took over the task of exploring Canada's High Arctic. The purpose was scientific rather than commercial. A prize of £20,000 was offered for the discovery of the Northwest Passage linking the Beaufort Sea and the North Atlantic Ocean. It took more than 100 years for the prize to be claimed.

In 1845 one of England's most noted Arctic explorers, Sir John Franklin, set out with two ships to try to sail through the Arctic Archipelago. The ships were last seen west of Greenland entering Lancaster Sound on July 26, 1845. Nothing was heard of or from the expedition again. For the next ten years a succession of rescue missions were dispatched to look for possible survivors; all without success.

On the chance that Franklin had penetrated through to western Arctic waters, Commander Robert M'Clure was sent there by way of Cape Horn, the Pacific Ocean and Bering Strait in 1850.

After his ship was crushed in the ice of the Beaufort Sea north of Banks Island, he continued his journey eastward by sled. He was rescued by other British Navy ships looking for Franklin and taken back to England via the eastern Arctic. It was therefore M'Clure, technically at least, who became the first man to traverse the elusive Passage. He and his surviving crew shared the £20,000 prize money.

The first person to actually "navigate" the Passage was Roald Amundsen who left his native Norway in a 75-foot herring vessel named *Gjoa*, in 1903, and spent two winters locked in the ice off King William Island. During this period of entrapment he made scientific observations of the nearby Magnetic North Pole. He continued his careful journey, threading his way through ice-choked channels and straits to reach the Beaufort Sea in 1906. (Amundsen acquired even more recognition in 1911 by becoming the first person to stand on the geographic South Pole.)

Staff-Sergeant Henry Larsen, skipper of the RCMP Arctic patrol vessel *St. Roche*, accomplished the feat of a west to east voyage 'over the top' from Vancouver to Halifax in the years 1940-42. This was followed by a return east-west Arctic crossing in 1944. The *St. Roche* was the last of the wooden-hulled ships to navigate the Northwest Passage. Ten years later the Canadian icebreaker HMCS *Labrador* became the first deep-draft vessel to make it through. Finally, and more recently (1969), the U.S. oil tanker *Manhattan*, with the help of the Canadian Coast Guard icebreaker *Sir Jo*[illegible] *MacDonald*, plowed through the ice fields of the eastern Arc[illegible]o the Beaufort Sea. The voyage was not a total success: before the *Manhattan* reached its home port on the Atlantic seaboard, sea ice had ripped a six-metre (20-ft) long gash in its hull.

The Overlanders

Although many British Navy captains and ships are immortalized on the map of the Canadian Arctic, so are explorer-fur traders such as Samuel Hearne and Alexander Mackenzie. Hearne is the lesser known of the two men but his accomplishment was the more epic. His odyssey took place in the years 1770-72, starting from the Hudson's Bay Company (HBC) post at Fort Prince of Wales, across the river from present-day Churchill, Manitoba. Hearne walked almost 5,000 miles, exploring more than a quarter of a million square miles of what he called "The Barren Lands." The wilderness he traversed lay west from Hudson's Bay as far as Great Slave Lake and northward to the Beaufort Sea. Hearne suffered at the hands of his Indian guides who were often hostile toward him. (Surly or not, they led him to his goal, the copper deposits near the mouth of the Coppermine River.)

Alexander Mackenzie was a partner in the North West Company (an active rival of the HBC). His two great journeys of exploration began from Fort Chipewyan at the western end of Lake Athabasca. The first trip took him north to the Beaufort Sea; the second westward through the mountains. His goal was to discover a canoe route to the Pacific. If he could find it, furs from the Canadian north-west could be shipped westward to China or, if the better market was in Europe, back east through Montreal. (The proposed canoe route through the Cordilleras never became practical but the exploration of the Mackenzie River was of great significance; it linked the resources of the river's drainage basin, which includes large areas of British Columbia, Alberta and Saskatchewan, with those of its delta and the Beaufort Sea.)

Lake Athabasca drains into the Peace River at the point where the easterly flowing Peace bends to the north and becomes the Slave River (which empties into Great Slave Lake). The young fur trader had two options: to follow the Peace upstream due west through the Rocky Mountains and possibly to the sea; or to follow it downstream through Great Slave Lake and into the mighty river which, Mackenzie hoped, would bring him to the Pacific at a high latitude. He chose to go downstream. The official reason for the trip was to extend the territory of his company's trading operation. Mackenzie wanted to offset the efforts of Samuel Hearne who, during his 1772 journey to the Coppermine River, had induced the Indians of the Athabasca region to trade their furs at Fort Prince of Wales on Hudson's Bay.

The year was 1789. Unlike Hearne, Mackenzie was leading a full-scale expedition. He had freight canoes, voyageurs to paddle them and Indian women to make moccasins and to fish. The birch canoe was a triumph of design and construction. It came in all sizes, the largest of which were about 11 m/36 ft in length with a two m/six ft beam (or width). These could carry up to five tons of cargo, along with the crew of ten men. At portages, of course, everything had to be carried. The 700 kg/1,500 lb canoe was shouldered by six men. Where the ground was level — and carrying places seldom were — the weight amounted to 115 kg/250 lbs per man. Mackenzie was travelling "light": guns and ammunition; tents; fish nets; a few trade goods intended for presents to Indians along the way; a sextant and a few bags of pemmican as emergency rations.

Mackenzie's meticulous journal records the departure from Fort Chip' at 9 o'clock in the morning of June 3, 1789:

> *"The crew consisted of four Canadians, two of whom were attended by their wives, and a German; we were accompanied also by an Indian,*

who had acquired the title of English Chief, and his two wives, in a small canoe, with two young Indians; his followers in another small canoe."

(English Chief had been one of the large group of Indians who led Hearne to the mouth of the Coppermine 17 years earlier.)

Their route took them to the 50 km/30-mile-long Quatre Fourches River which they followed downstream to the Peace (which at this point becomes the Slave River). It was springtime and between the pelting rain storms and seasonal snow melt, the current in the Slave was torrential. During the pellmell descent of the 400 km (240 mi) river (they made it in one day), the expedition was in constant danger from ice pans and drifting trees. They had to portage six times around rapids. Mackenzie lost one of his canoes at a waterfall.

Arriving at Great Slave Lake, Mackenzie was thwarted by the sheet of winter ice which still covered Canada's second-largest body of fresh water. The ice remained until June 21, summer solstice, when strong southerly winds cleared it out.

On the north side of the lake the expedition got lost searching for the exit river. Their Indian guide, Red Knif *(sic)*, led them into Yellowknife Bay in error. The Journal for Saturday, June 27:

> *By 3 this morning we were under way after a very restless Night being tormented by Musquitoes . . . our guides quite at a loss they do not know what course to take he says its 8 winters since he has been here, that this Bay is much like the Entrance of the River in consequence we steered down the Bay about W.S.W. Course until we got in amongst fields of Broken Ice still we could not see the Bottom of the Bay nor could we proceed. The Fog coming on made it very difficult for us to get to an Island S.W. of us, it was near dark when we landed upon it and camped."*

By skirting the shoreline they eventually reached the western end of the lake and found the river which would take the explorer's name. From that point their progress was rapid, averaging 160 km (100 mi) a day until they reached the delta of the river. Not that Mackenzie recognized it as such.

> *"July 10, 1789: Here the river widens and runs through various channels, formed by islands, some of which are without a tree, and little more than banks of mud and sand; while others are covered with a kind of spruce fir . . . So various were the channels of the river at this time, that we were at a loss which to take."*

Mackenzie was confused as to his location and beginning to doubt whether he would reach the Pacific Ocean after all. To the west, "*running to the Northward as far as we could see,*" were the snow-topped Rockies. At noon hour of that day he was able to take the observation he needed to calculate their latitude: 67° 47′ . . . "*which is further North than I expected, according to the Course I kept, but the difference is partly owing to the Variation of the Compass which is more Easterly than that I thought. I am much at a loss here how to act being certain that my going further in this Direction will not answer the Purpose of which the Voyage was intended, as it is evident these Waters must empty themselves into the Northern Ocean.*"

They continued into the delta for two more days until they were stopped by ice. They camped on an island and climbed to the highest part of it to look ahead. "*We could see the Ice in a whole Body extending from the S.W. by Compass to the Eastward as far as we could see.*"

BRIAN SMILEY

▲ Aerial of Beaufort Sea coastline shows patterned terrain and sea ice.

The next day they spotted beluga whales among the ice pans and, without thinking of the risk to their birchbark canoes, chased the whales. Fog closed in and ended their sport. After a few more days of searching for Eskimos and not finding any, a disappointed Alexander Mackenzie ordered the expedition about.

They were 2 000 km (1,250 mi) from Fort Chipewyan, and it was 'up hill' all the way. Most of this return journey was on foot, the voyageurs towing the canoes from the shoreline and wearing out moccasins at a rate of a pair each per day. Mackenzie's final notations for the journey read: "*September 11. Embarked at half past 4*

AM, froze hard last Night, cold weather throughout the Day, Appearance of Snow. September 12. The Wind veered to the Westward, and as strong as we could bear it with high Sail, which wafted us to Fort Chipewean by 3 oClk PM here we found Mr McLeod with 5 Men busy building a new House 102 Days since we left this Place."

The Trade

Men such as Hearne and Mackenzie depended on the Indians to guide them and provide food such as fish on the long journeys. For their part, the natives were usually glad to do so: only through the fur traders could they obtain the blankets, needles, guns, pots, knives, files and hatchets they found so useful. The natives could hunt and fish better than the white traders but these strangers could calculate time, distances, geographical locations; they wrote in journals, drew detailed maps and planned, at length, for future operations.

In historic terms, the contributions to Canada of both Samuel Hearne and Alexander Mackenzie are great. Thanks to their efforts, the broad outlines of the northernmost portions of British North America were charted. Mackenzie may have been disappointed at having reached the "Northern" Ocean that summer of 1789 but he was well aware that he had pre-empted the area for Canada against the then-possible claims of both Russia and the United States. He furthered this purpose, in 1793, when he walked out of the mountains and the bush at Bella Coola, on the British Columbia coast; the first white man to traverse the continent north of Mexico.

The River

The Mackenzie is one of the world's greatest rivers. Although it is considered as "starting" at the western end of Great Slave Lake, the Mackenzie actually has its headwaters much farther south (Figure 2). It begins in the Rocky Mountain Trench, just west of the main range of the Rockies, at 56° North Latitude, where the Finlay and Parsnip rivers join (in B.C. Hydro-made Williston Lake), to form the Peace River. The Peace flows eastward into Alberta where it hooks north until it hits the low Caribou Mountains height-of-land which deflects it east again. In Wood Buffalo National Park, two lakes: Claire and Athabasca, drain into the Peace just before it swings abruptly north. Here is where Alexander Mackenzie joined it for the trip down the Slave (note the name change here), to Great Slave Lake and down the exit river named after him. Despite its

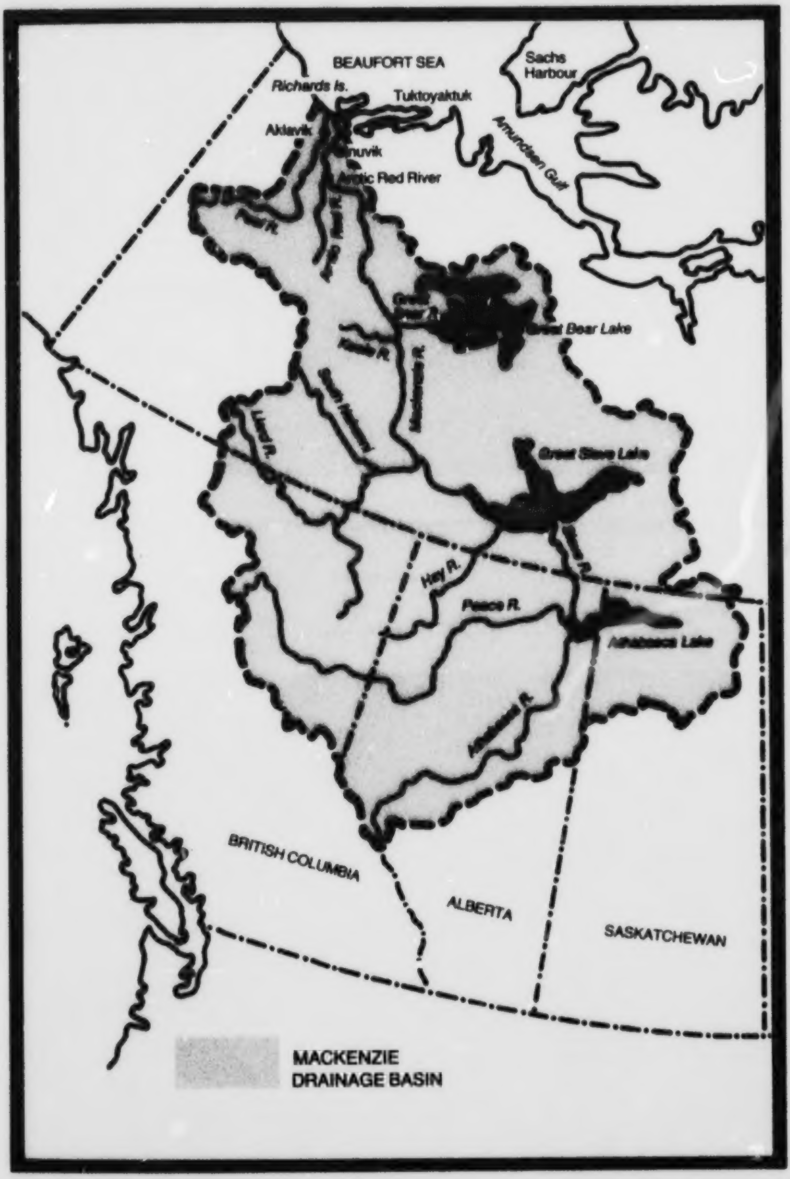
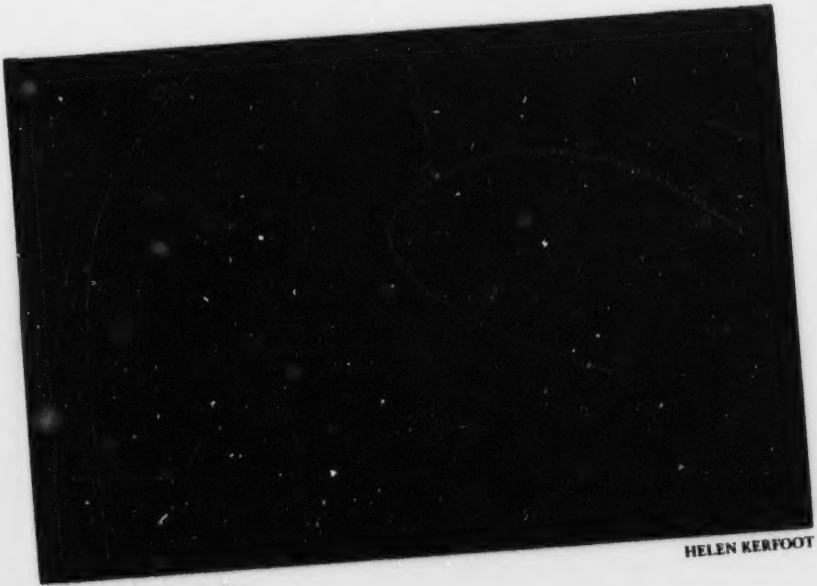

BEAUFORT SEA
Sachs Harbour
Richards Is.
Tuktoyaktuk
Aklavik
Inuvik
Arctic Red River
Amundsen Gulf
Peel R.
Great Bear R.
Great Bear Lake
Keele R.
Mackenzie R.
South Nahanni R.
Liard R.
Great Slave Lake
Hay R.
Peace R.
Athabasca Lake
Athabasca R.
BRITISH COLUMBIA
ALBERTA
SASKATCHEWAN
MACKENZIE DRAINAGE BASIN

Figure 2

ROD FORBES

▲ Mackenzie Delta, Big Fish River, Richardson Mountains in background.



HELEN KERFOOT

▲ Mackenzie Delta.

three names, this is all one river: from north-central British Columbia to the Arctic Ocean.

The river known as the Mackenzie is the northern portion of the system and is about 1 500 km (900 mi) in length from the outlet of Great Slave Lake to its mouth on the Beaufort Sea. The runoff flow down the Mackenzie fluctuates greatly between spring freshet and fall drought. The influence of the turbid, warm and fresh water of the Mackenzie on the biological life of its delta, estuary and adjacent coastal areas of the Beaufort Sea is important and, as yet, not entirely understood.

Delta

The broad delta of the Mackenzie is a maze of meandering channels and lakes, much of it low lying and subject to spring flooding (Figure 3). Silt carried down by the river has created vast, partially submerged plains extending far out to sea. The delta is of two geological ages: the modern, or recent delta which is

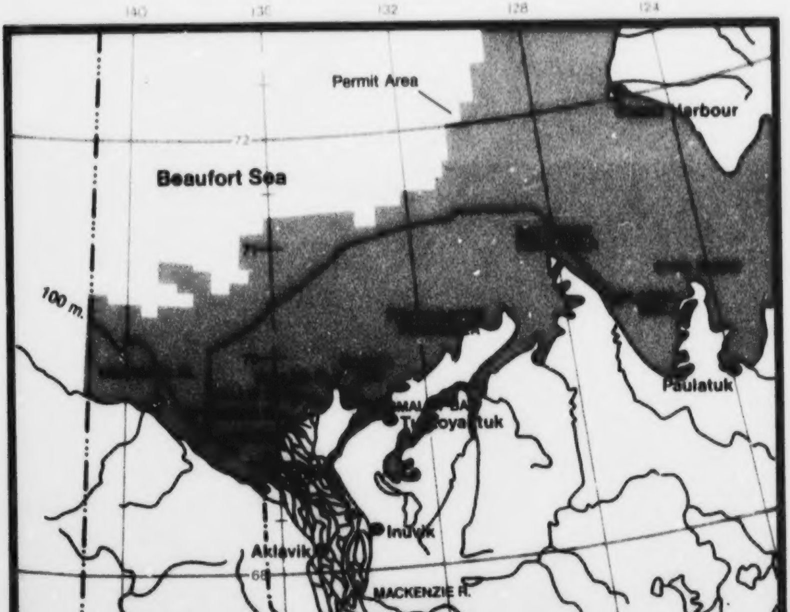
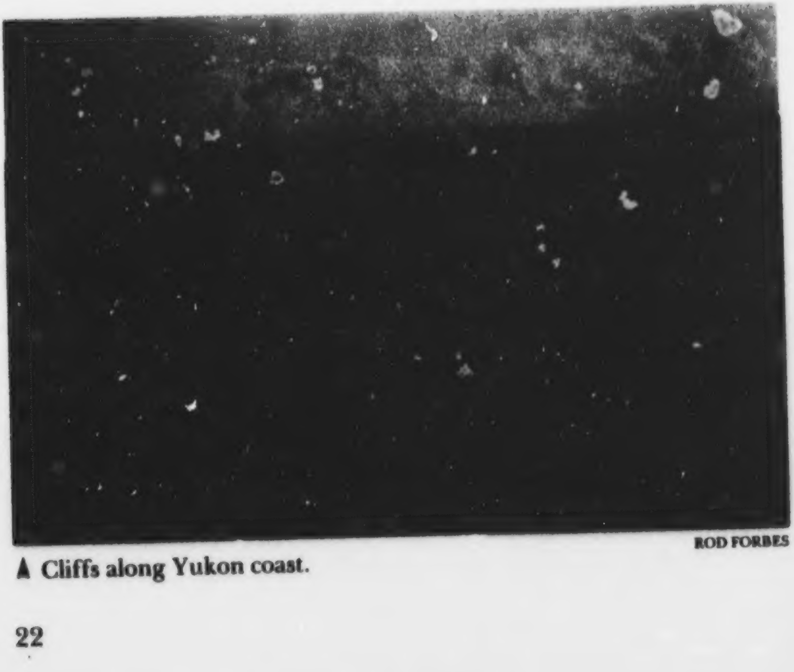

140
136
132
128
124
Permit Area
Harbour
72
Beaufort Sea
100 m.
Paulatuk
Tuktoyaktuk
Inuvik
Aklavik
68
MACKENZIE R.

Figure 3: Shaded portion shows offshore drilling permit areas (1978).

JIM BUNCH

▲ Pingo in Mackenzie Delta.

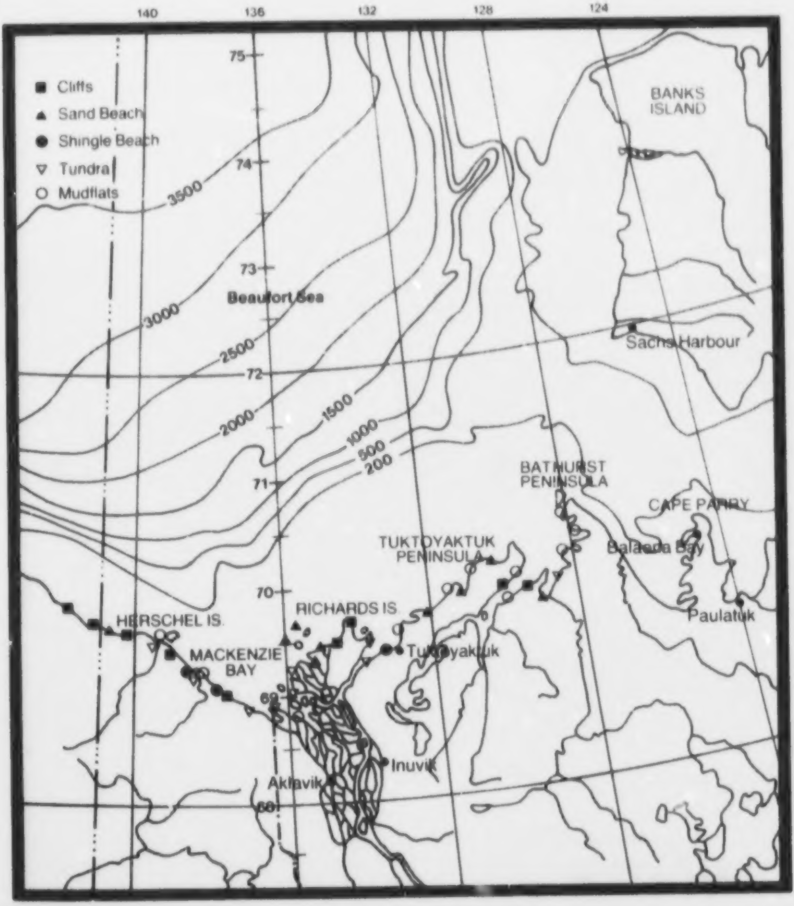


ROD FORBES

▲ Cliffs along Yukon coast.

continuously being deposited; and the Pleistocene coastlands, formed during the last great Ice Age (1.7 million years ago). Richards Island, the coast of the Tuktoyaktuk Peninsula, and the outlying islands in Mackenzie Bay, consists of Pleistocene sediments.

Elevation above sea level in the Mackenzie Delta does not exceed 30 m (100 ft), and is gently sloping except where undercutting and slumping (due to permafrost melt), have occurred. East of the Delta, along the Tuktoyaktuk Peninsula, the coast is a succession of spits, sandbars and giant frost heaves known


140
136
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124
75
74
73
72
71
70
69
68
■ Cliffs
▲ Sand Beach
● Shingle Beach
▽ Tundra
○ Mudflats
3500
3000
2500
2000
1500
1000
500
200
Beaufort Sea
BANKS ISLAND
Sachs Harbour
BATHURST PENINSULA
CAPE PARRY
Balaena Bay
Paulatuk
TUKTOYAKTUK PENINSULA
RICHARDS IS.
HERSCHEL IS.
MACKENZIE BAY
Tuktoyaktuk
Inuvik
Aklavik

Figure 4: General shoreline types.

as "pingos." In contrast, the Yukon coastline to the west of the Delta is characterized by spits and lagoons, sand or shingle beaches, and steep cliffs of permafrost (Figure 4). These cliffs, some as high as 100 m (330 ft), are continually eroding and slumping under the combined action of waves and permafrost melt. Eroded mud, sand and gravel are carried along by shoreline currents to settle on the sea bottom in sinks, where opposing currents meet. Areas of sediment deposition are particularly common along the Yukon coast.

Estuary

Waters of the Mackenzie estuary are shallow, seldom exceeding depths of six m (20 ft) as far offshore as 25 km (15 mi). The estuary varies with the seasons and from year to year. Changes

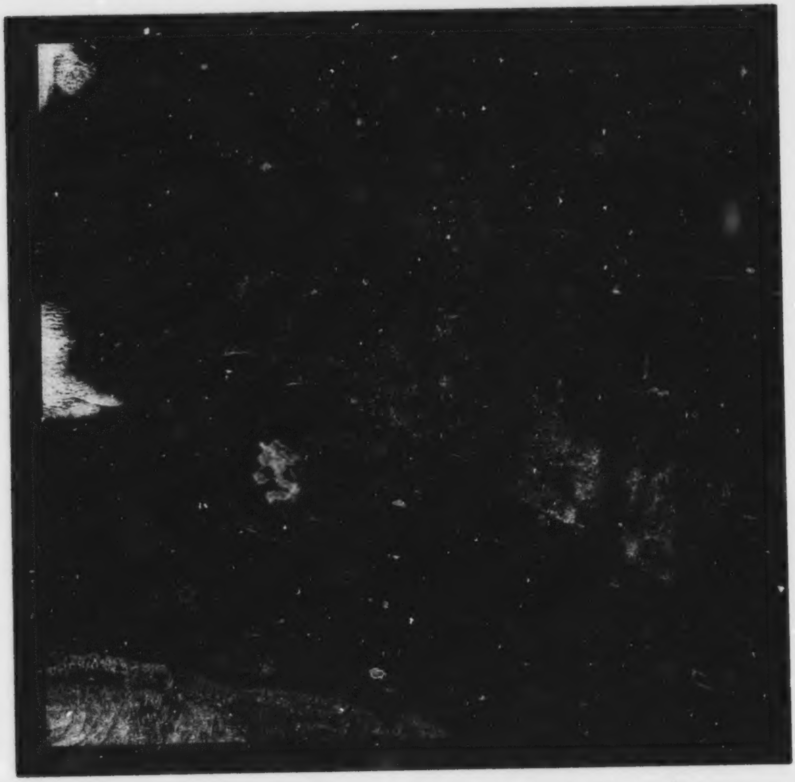


Figure 5: Satellite photograph of the Mackenzie River plume (8 September 1973).

occur with the rise and fall of water levels in the river but the estuary is also affected by winds, tides, and ice cover. The river's influence on the estuary is greatest at the time of peak freshet, around the end of May; minimum flow occurs in December.

The summer flow of fresh, warm river water often spreads widely over the denser, colder, sea water layer. This results in a tongue of frigid sea water protruding shoreward beneath the warmer surface layer of fresh water. In late winter, the slow-flowing Mackenzie drains relatively clear water into the Beaufort Sea. During peak spring run-off, this discharge increases eight fold or so; but now the water is muddied by silt. The huge cloud of drifting sand and silt particles can easily be seen and photographed from the air. It is known as "the plume" and is an obvious outer boundary of the Mackenzie estuary (Figures 5 and 6).

The water shows a wide variation in salt content (zero to 34

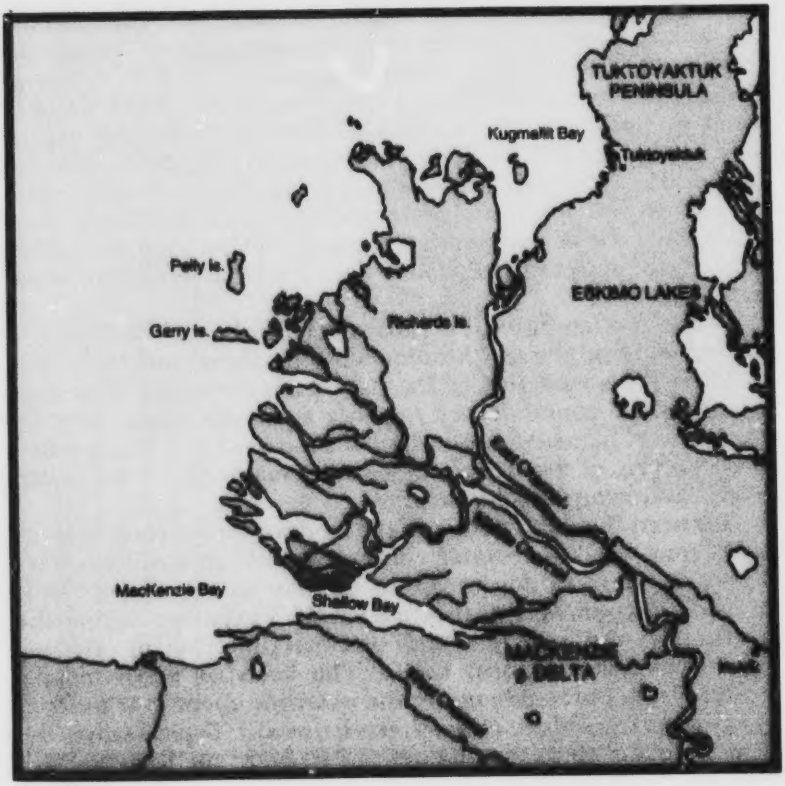

TUKTOYAKTUK PENINSULA
Kugmallit Bay
Tuktoyaktuk
Pelly Is.
ESKIMO LAKES
Garry Is.
Richards Is.
East Channel
Middle Channel
MacKenzie Bay
Shallow Bay
MACKENZIE DELTA
Inuvik
West Channel

Figure 6: Area shown in Figure 5.

percent), and temperature (minus one to plus 18°C). In general it may be said that the saltiness increases and temperature drops with distance from shore and with depth of the water. Offshore surface waters — to a depth of about 200 m (660 ft) — are of Arctic Ocean origin. Below that lie waters that come from the Atlantic.

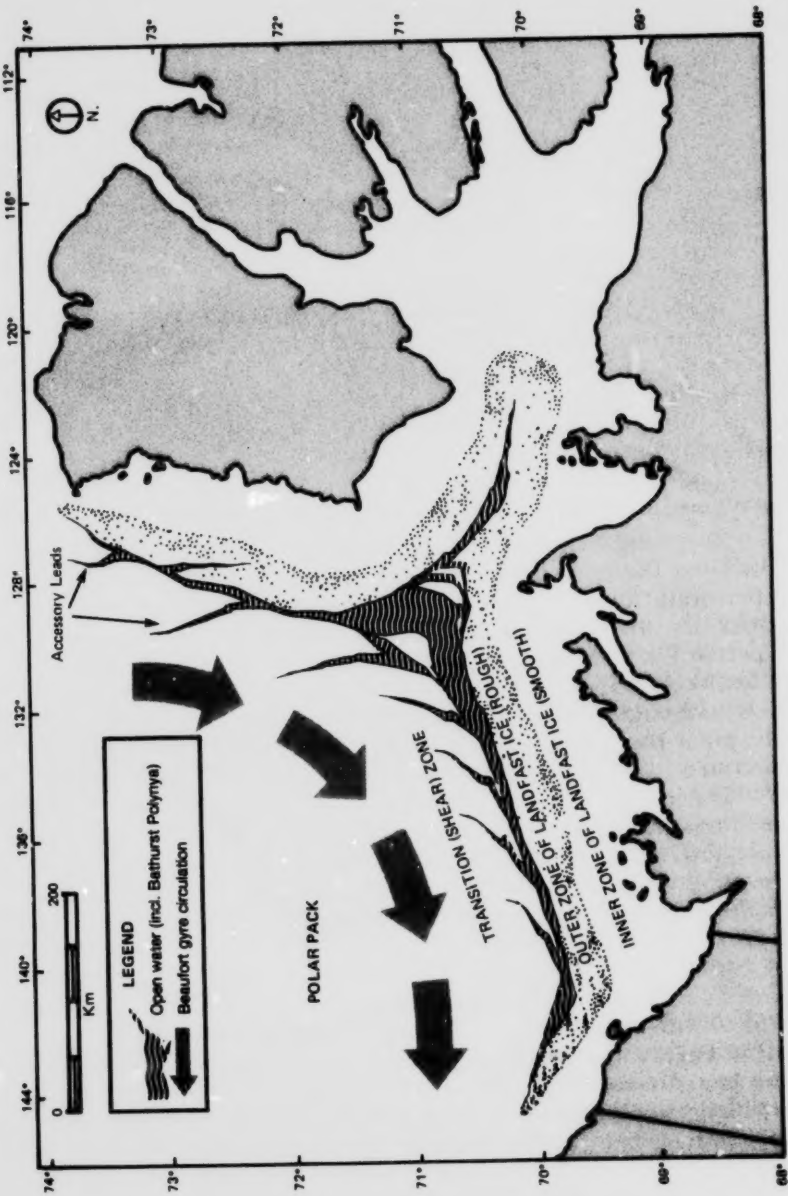
Sea ice

North of the Mackenzie Delta, and usually beyond the continental shelf, the pack ice of the Beaufort Sea is driven slowly and relentlessly on a large scale by the winds. Most of these winds are produced by a stationary high pressure air mass over the Canada Basin. This typical Arctic weather system produces a clockwise circulation of pack ice called the Beaufort Gyre (Figure 7). In addition to imparting a slow, sporadic, westerly movement of the pack ice in the southern Beaufort Sea, the sluggish spiral current moves floating ice into the vicinity of the Mackenzie Delta.

In autumn, landfast ice begins to form along the shore, attaining thicknesses of up to two metres (six feet). With the onset of winter, it may extend offshore for 50 km (30 mi). Beyond that is found the multi-year ice pack. This floating ice sheet averages three metres (ten feet) in thickness. In summer, ice melts from the upper side of the pan exposed to the sun but, a roughly equal amount of new ice is added to the underside in winter. The continuing cycle of summer thawing and winter accretion ensures that even the oldest ice in the polar pack is seldom more than seven years of age.

While the landfast ice is relatively smooth, the polar pack is covered with ridges and hummocks both above and below the waterline. This rumpling of the pack ice is the result of endless fracturing and jamming back together again that takes place the year round. The ceaseless grinding of the ice ensures that as much as five percent of the Beaufort Sea will remain open water at any given time during the cold winter.

Between the polar pack and the landfast ice is a transition, or shear, zone which in winter contains mobile seasonal pack ice (Figure 7). Here rafting occurs in the new ice as one surface is jammed under another. If the ice is too thick to permit rafting, the ice crumbles and is wedged both upwards (into pressure ridges), and downwards (to form keels). The keels of newly-formed pressure ridges protrude under the waterline about four times as far as the surface ridges, or 'sails', reach upward. Typical sails in the shear zone are up to four metres (13 ft) high; the undersurface keels 16 m (52 ft) deep. (Keels of 40 m/130 ft-depth have been recorded.) The bottom of the Beaufort Sea in shallow areas is criss-


74°
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116°
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144°
N.
Accessory Leads
LEGEND
Open water (incl. Bathurst Polynya)
Beaufort gyre circulation
0
200
Km
POLAR PACK
TRANSITION (SHEAR) ZONE
OUTER ZONE OF LANDFAST ICE (ROUGH)
INNER ZONE OF LANDFAST ICE (SMOOTH)

Figure 7

crossed with the score marks of these plow-like keels. Any marine life, if it is to exist here, must survive such natural damage.

Weather

Arctic weather is known for its extremes. In autumn the coast is plagued by the low clouds and fog which form when cold air from the polar pack meets the expanse of warmer open water. During winter, continuous darkness envelopes the area. It is a time when the surfaces of land and ocean are subjected to maximum cooling. Lowest temperatures are recorded in February when the mean approaches -35°C.

The ice season has an average duration of 280 days. For this length of time, most of the Beaufort Sea will be under snow-covered ice. Usually, as mentioned above, as much as five percent of the Beaufort can be expected to remain open (Figure 7). Air pressure differences will influence the size of the cracks, leads and polynyas which intermix with the shifting floes. During an exceptionally cold year (such as occurred in 1974), the Beaufort may remain almost completely covered by ice.

Warming is delayed in the spring by the reflective snow cover. But once the snow has melted the ice soon warms. In early June open water begins to appear on the west side of the Mackenzie Delta. By the end of the month, the eastern part of the estuary is open as far as Tuktoyaktuk. Gradually the ice recedes along the Yukon coast. The region west to Herschel Island breaks up by mid-July, although this area is seldom totally free of ice. Farther west, the polar pack remains close to the Alaskan coast throughout the summer.

During the summer, temperatures average 5°C but maximum readings can go to 30°C. Due to continuous daylight in June and July, total solar energy in the Arctic equals that of some temperate latitudes. Annual precipitation is light (equivalent to only 12.7 cm/five inches of rain), and is almost equally divided between rain and snow.

Tides are small in the Beaufort Sea. Summer tides average from 0.2 m (eight inches) at Herschel Island in the west to 0.5 m (20 in) at Tuktoyaktuk in the east. However, wind storms, especially in the late summer when ice cover is minimal, subject the gently shelving coastline to storm surges. Water levels higher than two m (6½ ft) have been recorded at the outer fringe of the Delta during periods of high onshore winds. Storm surges can develop rapidly. The subsequent flooding can threaten local fishing and hunting camps and accelerate shoreline erosion.

▲ Storm surge driftwood deposit near Kay Point.

ROD FORBES

Life forms

The Arctic Ocean (including the Beaufort Sea), has low biological productivity compared to the temperate waters of southern Canada. Yet the area is not a "biological desert". Although the overall total of animal and plant species is relatively low, the number of individuals can be large.

High dissolved-oxygen levels have been recorded in surface Beaufort Sea waters, especially in the offshore zone. Because warmer water has a lower capacity for dissolved gases than does cold, the Mackenzie River tends to reduce oxygen content in the murky waters of the estuary. In general, Arctic rivers are low in nutrients and dilute rather than add to the supply of the coastal waters into which they drain. The Mackenzie River, however, after flowing north from Great Slave Lake, is a significant source of mineral nutrients for the southern Beaufort Sea.

The ocean can be regarded as having a surface producer zone where sufficient sunlight penetrates in summer to permit plants to flourish; in much deeper waters, the only consumers found are dependent on the dying plants. The deeper waters show much less seasonal variation than do the surface waters which fluctuate widely in temperature, nutrients and salinity. During the dark months of winter, under complete or partial ice cover, plant production is at its lowest.

With the arrival of light in early spring, an algal community proliferates at the undersurface of the ice. Later in the season, microscopic plant growth (phytoplankton) in the water increases dramatically, often forming dense algal blooms of a single species. During the abbreviated Arctic summer, this passively floating plant life, and the weakly swimming microbial animals (zooplankton) which feed on it, form the base for a number of short yet important food chains upon which higher animals, including man, ultimately depend (Figure 8).

Arctic fox, polar bear, bearded and ringed seals, reside year round in the Beaufort Sea area; other mammals such as the bowhead and white whales emigrate from the region in winter. Most of the 50 or so species of birds which frequent the Beaufort Sea are temporary visitors; yet without the energy reserves they build up in Arctic waters, they could not make the arduous migrations to overwintering sites in the southern United States and South America.

Many of the fish species found in nearshore surface waters are anadromous. These fish, which include the Arctic char and many members of the whitefish family, return each year from the sea to spawn or overwinter in fresh water. Lake trout, native to fresh water, make occasional sorties into brackish coastal waters. Most of the saltwater fish are small, bottom-dwelling species, adapted to living year round in the Beaufort Sea.

Inuit

The Inuit of the western Arctic are the descendants of two aboriginal groups: the Inuit of North Alaska, and those of the Mackenzie Delta. To the east of Amundsen Gulf were the Copper Inuit. The Alaskan natives were split into two groups which differed in their hunting orientation. There were the whale hunters of the coast, and the inland caribou hunters of the Brooks Range area. At the time of Hearne and Mackenzie, there were about 5,000 Alaskan, 2,000 Mackenzie, and 1,000 Copper Inuit.

Alexander Mackenzie explored his river in 1789; the following year he sent his cousin, Roderic Mackenzie, to build a trading post on a small island at the entrance of the Mackenzie River (western end of Great Slave Lake). More posts were built, extending the North West Company's commercial reach northward along the Mackenzie Valley and closer to the Inuit. These included the posts at Marten Lake (1793); Fort Providence 130 km (80 mi) below Great Slave Lake in 1796; and Fort Simpson, at the mouth of the Liard River in 1804. The next year another trading post, Fort Good Hope, was opened near the mouth of the Hare River. It was here

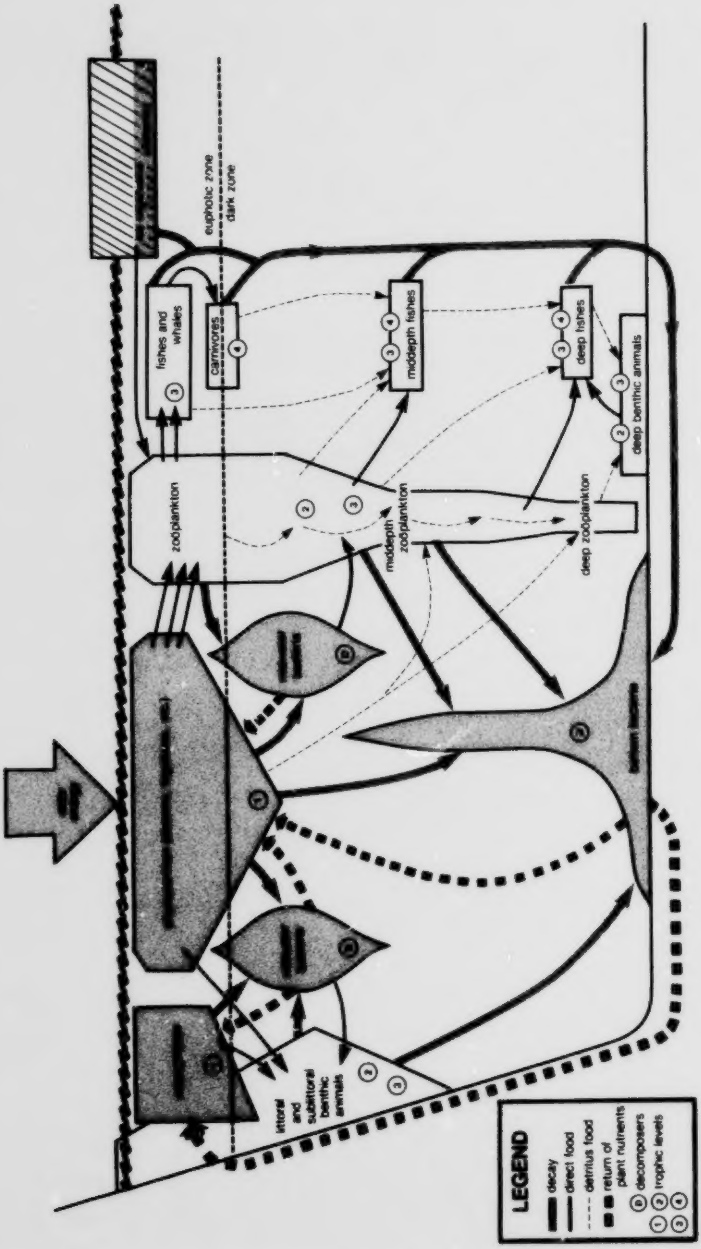

euphotic zone
dark zone
fishes and whales
carnivores
middepth fishes
deep fishes
deep benthic animals
zoöplankton
middepth zoöplankton
deep zoöplankton
littoral and sublittoral benthic animals
LEGEND
decay
direct food
detritus food
return of plant nutrients
decomposers
trophic levels

Figure 8: Ocean food chain.

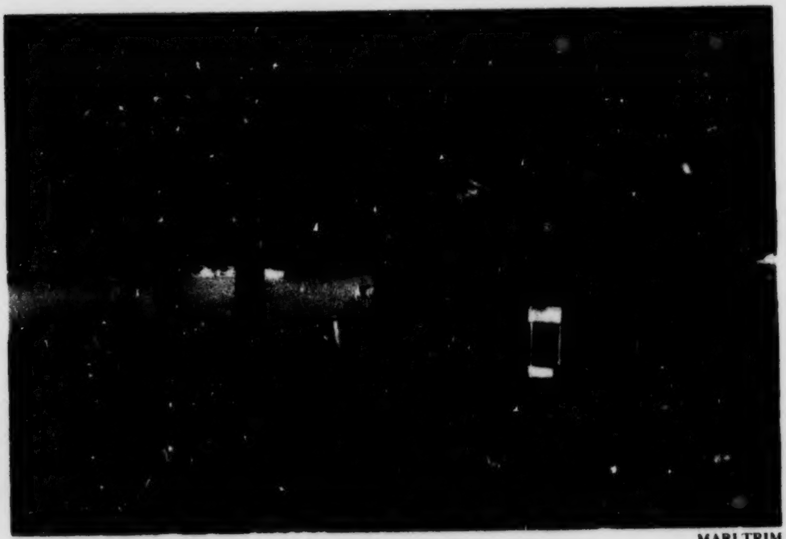
MARJ TRIM

▲ Drillship in Beaufort Sea.

that Mackenzie Delta Inuit learned that the arctic fox, which was not of much use to themselves, was of great value to the white man. They also were introduced to European trade goods.

Of lasting significance to the development of the present-day Inuit was the arrival of the whaling fleet from San Francisco. The harvesting of bowhead whales began in Alaskan waters in the 1850s and shifted to Herschel Island in the Mackenzie region in the 1890s. The whalers needed the Inuit to hunt caribou and catch fish for them. In trade for meat, the whalers gave the Inuit rifles, boats, tea, coffee, flour and sugar; just about anything Americans had or could produce. The Inuit helped the whalers hunt the bowhead whales, worked aboard their ships, socialized with them on shipboard and on land. They learned to speak "American", to deal in dollars, to handle white man's technology.

With the collapse of the whaling industry in the early years of this century, part of the Inuit economy in the western Arctic also changed. The wage economy was replaced by a resurgence in the fur trade following World War I (1918). In the 1920s muskrat skins brought the Inuit trapper $1 each; white fox sold for $50. Family incomes sometimes totalled $10,000 or more (and this at a time when the average factory worker in North America earned $1,000 a year). But by the end of World War II (1945), fur prices had fallen to such a level — and animals became so scarce due to over-hunting — that this era of fur trade had effectively ended.



MARJ TRIM

▲ Inuit fishing camp on shore of Beaufort Sea.

In the 1950s the construction of a line of radar stations was completed across the northern coast of Canada. The purpose of this Distant Early Warning Line, or DEW Line, was to warn of incoming flights of Russian missiles aimed at North American cities. In conjunction with this international defence activity, federal government agencies and their staffs moved in and "instant towns" such as Inuvik were built. This industry boom continued into the 1960s with petroleum exploration in the Mackenzie Delta region. The search for oil in the shallows of the southern Beaufort Sea is, at time of writing, still ongoing.

For most arctic residents there are two principal concerns: 1) the preservation of the environment; and 2) the well-being of the native northerners. In considering these points we must keep in mind that most northerners want some form of industrial development. Also, northerners value their surroundings and insist that the extraction of mineral resources not be done in an attitude of development-at-any-price. As for the renewable resources such as wildlife, the native peoples of the Yukon and Northwest Territories are still, to a varying extent, dependent on the available fish, whales, seals and bears.

The Mackenzie River

One cannot help but be awed by the size and importance of the Mackenzie River. Its drainage basin (Figure 2), encompasses some 1 900 000 square kilometres (km^2) (730,000 sq mi), and represents the second largest river system in North America; surpassed only by the Mississippi/Missouri system. The distance from the source of the Finlay River in British Columbia to the mouth of the Mackenzie on the Beaufort Sea is 4 250 km (2,635 mi); from another headwater source, the Athabasca River in western Alberta: 3 500 km (2,205 mi). Few Canadians appreciate that the drainage area and length of the Mackenzie exceed those of the Great Lakes and the St. Lawrence River. In fact, the Mackenzie watershed covers one-fifth of the total land area of Canada (equivalent to the combined land areas of Great Britain, France, Germany, Spain, Portugal and Italy).

Roughly 43 percent of the Mackenzie basin lies in the Northwest Territories; 23 percent in Alberta; 17 percent in British Columbia; ten percent in the Yukon and the remainder in Saskatchewan. The Mackenzie and its tributaries contribute an estimated seven percent of North America's freshwater flow to the adjacent oceans. Major lakes in the Mackenzie system are Athabasca, 8 000 km^2 (3,000 sq mi); Great Bear, 31 000 km^2 (12,000 sq mi); and Great Slave, 28 500 km^2 (11,000 sq mi), having a combined surface area of some 63 500 km^2 (26,000 sq mi). In comparison, Lake Ontario is 19 500 km^2/7,500 sq. mi.

Three major tributaries are the Peace, Athabasca and Liard rivers. The Athabasca originates in the Rocky Mountains near Jasper, Alberta, and flows into Lake Athabasca. The Peace rises in the Rockies of northeastern British Columbia and flows into Great Slave Lake while the Liard starts in the southeastern Yukon, joining the Mackenzie at Fort Simpson. Other important rivers flowing into the Mackenzie are the Nahanni, Keele, Arctic Red and Peel from the mountains to the west and Great Bear River (draining Great Bear Lake), from the east.

The eastern side of this great basin lies in the Canadian Shield, predominantly wooded and with numerous lakes, swamps and muskeg. The Great Bear, Great Slave and Athabasca lakes sit astride this part of the basin. The western side is in the Cordilleran region made up of the Mackenzie and Richardson mountain ranges. The middle part (roughly one-third) through which the Mackenzie River flows is known as the Flat Central Plains area. It is largely forested by jack pine and spruce and possesses extensive stretches of muskeg.

The permafrost (frozen ground) is continuous from Arctic Red River north and discontinuous but widespread to the south. Boreal forest lines the Mackenzie River for much of its length. The surrounding area is thickly forested south of Norman Wells but mostly tundra from there north to Richards Island in the Delta.

There is a wide variation in climate within the Mackenzie Basin; overall, it tends to have a milder climate than those parts of Ontario, Manitoba and Quebec which lie in the same latitudes. The summers are cool and short.

Annual precipitation varies from less than 13 cm (five in) over the Beaufort Sea to 39 cm (15 in) along the Mackenzie and up to 75 cm (30 in) in the mountains west of the river valley. In summer, the thawing of the permafrost's surface layer gives the impression of an extremely wet area.

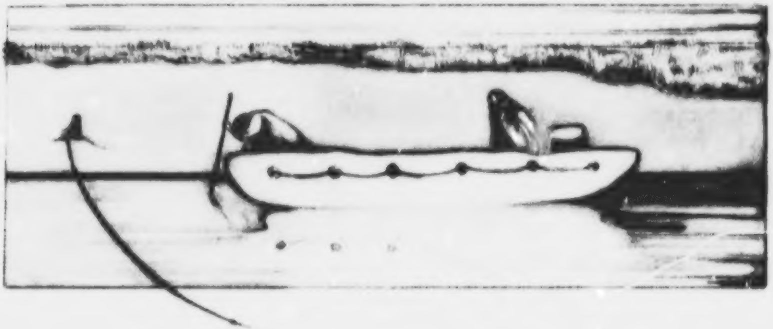
Minerals in stream banks through which the river and its tributaries flow are released into the water. Dissolved solids increase from a mean value of about 182 mg/liter in Great Slave Lake to 202 mg/liter as the Mackenzie enters the Delta. The river water contains relatively high concentrations of phosphorus, nitrogen, copper, lead and zinc and is also relatively high in organic carbon (median value of seven mg/liter) due to its passage through areas of muskeg.

Mean annual flow exceeds 11 500 cubic metres (m^3) per second or over 30 billion m^3 total. The low flow period extends from December to April while the largest discharge occurs between May and September. Over the average year, an estimated 218 million tonnes of sediment move into the Delta region from upriver. Maximum loads may exceed 2.5 million tonnes/day in June. This silt loading is heaviest north of Fort Simpson where the Liard enters the Mackenzie.

Mackenzie watershed rivers transport large amounts of suspended matter in a short time compared to temperate and tropical rivers. For example, the Mackenzie at Norman Wells has an annual discharge of 247 km^3 and drainage area of 1 570 000 km^2 whereas the Mississippi has 563 km^3 and 3 220 000 km^2 respectively; the rate of transport of suspended sediment is roughly equivalent in these two great rivers.

The Mackenzie's sediment load is made up of inorganic silts

(60 percent) and clays (30 percent) with some sand-sized particles also being transported. Such materials inhibit the growth of many aquatic organisms by altering the substrate of the streambed, abrading plants and animals, and reducing light penetration needed for photosynthesis. Generally, turbid rivers and lakes support a less abundant and diversified invertebrate fauna than do clearer waters.



Taking discharge measurements in a river channel.

The chemical constituents of the suspended sediments include calcium, magnesium, iron, zinc, lead and mercury. Waters of the Mackenzie range from medium to very hard. There is a rapid decrease in hardness values in late April when snowmelt waters enter the system. The Arctic Red and Peel rivers tend to increase the hardness of the mainstem water. Total hardness increases from roughly 90 parts per million (ppm) of calcium carbonate at Fort Simpson to values more than double these at Aklavik in the Delta.

Of the hundreds of millions of tonnes of sediment deposited in the Delta each year, about ten percent consists of sand, carried partly in suspension and partly as bed-load, while the remaining 90 percent is silt and clay borne entirely in suspension. The average suspended sediment load in lower Mackenzie River waters is approximately 350 mg per liter; during spring freshet it can increase to concentrations approaching 10 000 mg per liter. About half the annual deposit carried into the Delta originates in the Liard River; much of the rest comes from the other tributaries that flow in from the west side of the Mackenzie. Most of the Mackenzie River flow exits through the Delta via the main channel. The next greatest flow is via the Peel Channel, varying up to seven percent over the one-year period tested (as part of the Beaufort Sea Project). Beyond Richards Island, the current slows and the sediment ends up on the floors of Kugmallit, Mackenzie and Shallow bays.

Water temperatures in the main stream of the Mackenzie and its larger tributaries exceed 16°C in July and August. Temperatures in Kugmallit Bay on the coast reach 12°C in August but drop to below 0°C in winter.

The Mackenzie basin is so large that different climates exist in its upper (southern) and lower (northernmost) portions. Thus, while the ice season extends an average 180 days in the upper Mackenzie region, it is 280 days in the Beaufort Sea. Ice thicknesses in the lakes average 1½ m (five ft); in rivers one metre (three ft); while Beaufort Sea ice grows to two metres (seven ft) in thickness over one winter. Greater ice thicknesses will occur if there is light snowfall in the October to December period. Under an insulating layer of heavy snow, however, the ice will be much thinner.

The Mackenzie River generally clears of ice in a short period of time (within a matter of days). Break-up is an impressive phenomenon signalling the advent of spring. Many of the local settlements hold lotteries in which residents attempt to predict the exact time of break-up in their area. In Mackenzie Bay, waters are generally free of ice by the end of June, while clearing along much of the rest of the southern Beaufort Sea coast occurs by late July. The river usually rids itself of ice two to four weeks in advance of lakes in the system. However, such generalities can be wrong by several weeks, depending on the spring conditions.

Transportation

Population density in the Mackenzie basin is roughly one person per 130 km^2 (50 sq mi); (compare this with the average in southern Canada of five persons per square mile). Originally, settlements were established along the major waterways to accommodate the flourishing fur trade. Southerners were drawn north by the discovery of oil along the river at Norman Wells in 1919, the finding of gold at Yellowknife and radium at Port Radium in the 1930s, and by uranium and base metal deposits near Great Slave Lake in the 1940s. More recently, the petroleum reserves of the Mackenzie Delta/Beaufort Sea region have attracted still greater numbers of entrepreneurs.

In order to support these activities, barges from Hay River and Fort Simpson make the three-week round trip to deliver cargo of every description to major settlements along the Mackenzie River as far as Tuktoyaktuk. The river is navigable throughout its length. It averages 1.6 km (1 mi) in width and has a gradient of 15 cm (6 in) to the mile. As a means of transport, barges pushed by tugs is the least expensive. Between June and October, barges handle over a million tonnes of cargo (a large part being fuel supplies).

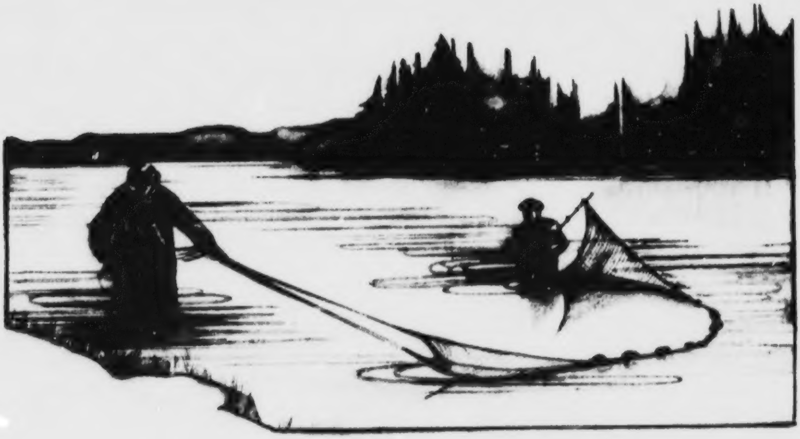
In winter (but not until March or April when the river ice is frozen to maximum thickness and can support tractor-trailers), ice roads are constructed between Inuvik, Aklavik and Tuktoyaktuk. More ice roads leading to various outlying exploration sites give access to materials brought up the Dempster Highway by truck. With the opening of the Dempster, the Mackenzie Valley became a year-round transportation corridor to the Beaufort Sea.

Fishes

Compared with other river systems at similar latitudes, the Mackenzie River supports a diverse fish fauna. To date, some 38 fish species have been found in the river and its tributaries north of 60° latitude; that is, in the Yukon and Northwest Territories. Some fish species found in the upper Mackenzie watershed are at the northernmost limit of their ranges in North America. They include Dolly Varden, lake cisco, white sucker, yellow walleye and mountain whitefish, among others.

Zooplankton (free-swimming invertebrates) are the link in the food chain between the primary producers and the higher trophic levels of fish, birds and mammals. They are found throughout the Mackenzie system. The most abundant — and most often observed in the stomachs of fish in the region — are rotifers, copepods and cladocerans. The numbers and types of benthic (bottom-dwelling) organisms increases the farther one goes upstream and away from the Delta. Also, tributary rivers flowing into the Mackenzie from the east support more benthos than do those coming in from the west. This is because the tributaries on the west drain mountainous terrain, flow faster and carry down heavier loads of suspended sediments. Sedimentation limits bottom life by burying aquatic organisms, interfering with respiration and eliminating habitat. The most common zoobenthos found in the Mackenzie system are chironomid larvae.

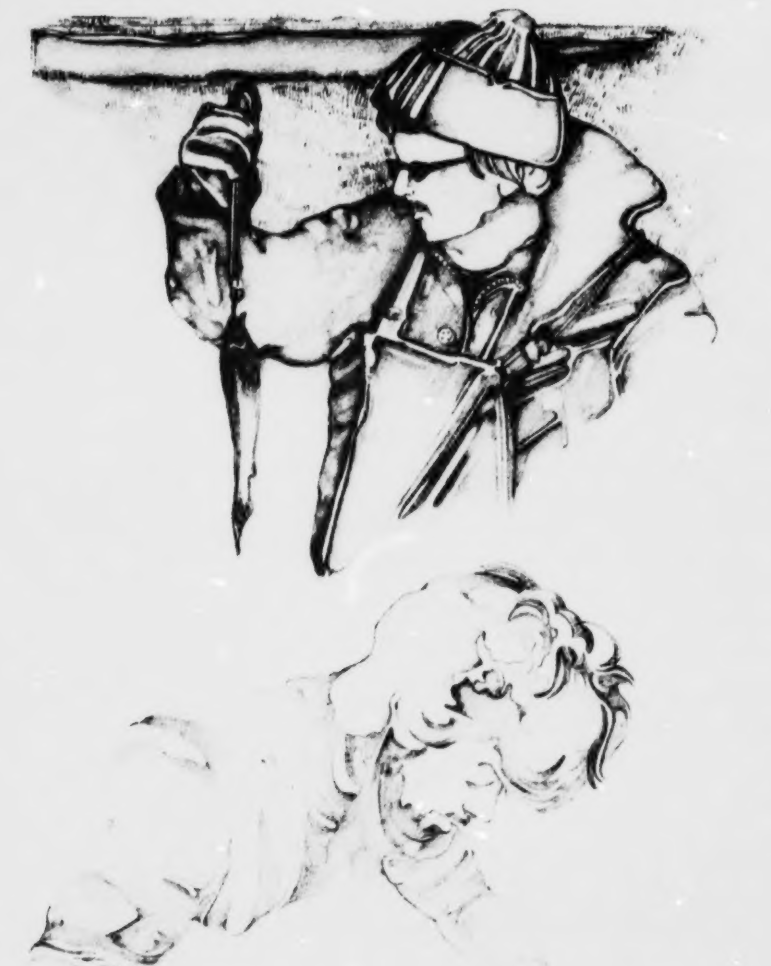
Even though primary and secondary production levels are lower here than for river systems in the world's temperate zones, fish are often found locally in great numbers. This is due to the migrations of anadromous fish from throughout the southern Beaufort Sea returning to spawning grounds or overwintering sites high in the watershed. Of the nearly 40 freshwater and anadromous fish species to be found in the Mackenzie system, some like the northern pike, Arctic grayling, inconnu and longnose sucker range the river's length while others are restricted to various locales. White suckers, yellow walleye, mountain whitefish and lake cisco, for example, are caught only in the southern half of the basin; broad whitefish, Arctic and least cisco are common only in the north.



Seining in river.

Statistics of fish catches along the Mackenzie River Valley date back to the late 1800s in the diaries of missionaries and in the notes kept by RCMP detachments concerning the fish needed to feed their sled dogs. Some recent data on the fishes of the Mackenzie River comes from environmental studies conducted in advance of proposed highway and pipeline projects. The federal Fisheries Department established four study bases in the Valley at Aklavik, Arctic Red River, Norman Wells and Fort Simpson in the early 1970s. About 65 percent of the total fish taken at the Aklavik test camp were Arctic cisco, humpback and broad whitefish. In Arctic Red River, 70 percent of the catch was made up of northern pike, Arctic cisco and broad whitefish. The Norman Wells and Fort Simpson catches were 85 percent Arctic grayling, longnose sucker and northern pike.

Table A compares the fish species present in a number of Mackenzie tributaries: Great Bear River (25 species); Rabbitskin River, an eastside tributary above Fort Simpson (19 species); Trail River, another eastside river below Fort Simpson (9 species); and the Rat River, a westside stream entering the Delta between Aklavik and Arctic Red River (13 species). The eastside tributaries, which have better water quality, support more species than do the larger but more turbid westside rivers.



Biologists study fish populations.

A comparison of fish species caught
by researchers in four contributaries
of the Mackenzie River.

	Great Bear River	Rabbitskin River	Trail River	Rat River
Arctic grayling	●	●	●	○
Arctic char	○			●
Lake trout	○			
Inconnu	○	○		○
Humpback whitefish	○	●	○	○
Round whitefish	●	○		●
Mountain whitefish	○	○	○	
Arctic cisco	○			○
Lake cisco	○	○		
Least cisco	○			○
Northern pike	●	●	●	●
Burbot	○	○	○	○
Yellow walleye	○	○	○	
Longnose sucker	●	●	●	○
White sucker	○	○		
Flathead chub	○			
Lake chub	○	○		
Longnose dace	○	○		
Spottail shiner	○	○		
Goldeye	○			
Slimy sculpin	○	○	●	
Trout perch	○	○	○	
Arctic lamprey	○	○		○
Ninespine stickleback	○			○
Emerald shiner		○		
Spoonhead sculpin		○		
Broad whitefish	○			●
Totals	25	19	9	13

● — Species most often caught

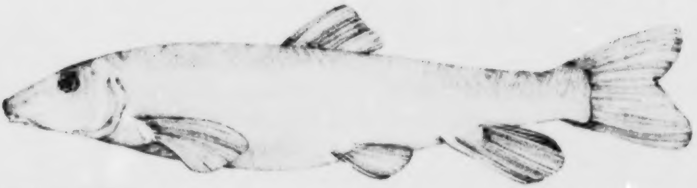
TABLE A

Species such as Arctic grayling, yellow walleye, northern pike and longnose suckers spawn in the spring soon after the ice goes out. The Arctic grayling is valued by sport fishermen but not as much by native northerners. This may be due to its relatively small size: it seldom exceeds 50 cm (20 in) in length. Grayling are distributed throughout the Mackenzie system but are more numerous in eastside tributaries south of Norman Wells. They mature in their fifth to eighth year and spawn on an annual basis thereafter. Their migration patterns between lakes, rivers and smaller streams are complex. Grayling feed on insects. Adult fish prey on chironomids (midge larvae), while juvenile grayling eat mostly trichopterans (caddisflies). Of course, this can vary from place to place, and year to year.

The yellow walleye is a large member of the perch family. It can grow to 78 cm (30 in) in length and river populations frequent the mouths of fast-flowing, clear-water streams in the southernmost parts of the Mackenzie basin. Not much is known of their migratory habits here. Specimens tagged and released near Arctic Red River have later been caught 300 km (185 mi) upriver from there while others were taken close to their release point as long as a year later.

Northern pike, which can grow to 120 cm (48 in) long, are one of the most abundant and widely distributed fish in the entire system. Like all pike, these prefer shallow weedy areas of lakes or creeks at places where shoreline vegetation has been inundated. The pike leave these habitats in fall to overwinter in the Mackenzie mainstem. In spring, they spawn at the mouths of tributary streams and in Delta Lakes. Noted hunters, (they prey on any type of smaller fish that swim by), they are not great travellers. Most tagged northern pike recaptured, have strayed no farther than 75 km (45 mi) from the point of release.

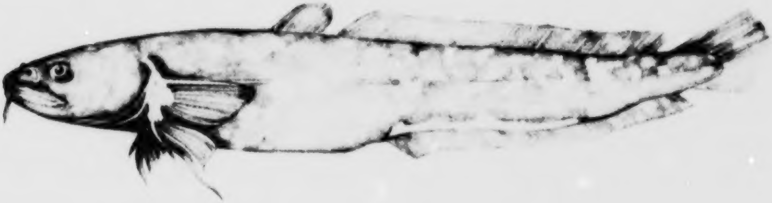
The longnose sucker averages 40 cm (16 in) at maturity. It is found all along the Mackenzie River but in greater numbers to the



Longnose sucker

south. Like the walleye, the longnose sucker is attracted by clear, fast-flowing streams. They are bottom feeders; food items include aquatic insects, amphipods, molluscs and plant materials. White suckers have similar life habits; they are found in the far south of the Mackenzie Valley and as far north as Fort Good Hope.

Goldeye prefer the turbid areas of the Mackenzie River and are most numerous in the Fort Simpson area. This species overwinters in the deeper water but, soon after the ice has gone out in the spring, migrates to its spawning grounds in stream pools or shallows of lakes. Adult goldeye (up to 50 cm/20 in) feed primarily on insects.



Burbot

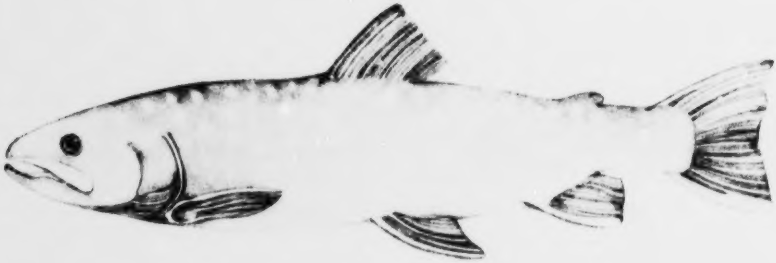
Burbot, the only freshwater member of the cod family, is found dispersed throughout the Mackenzie valley. Tagging data reveals that this species does not undertake distant migrations. Spawning takes place in the winter, under ice, probably on sand or gravel bottom. Adult burbot (up to 120 cm/4 ft. in length) are predators, feeding almost exclusively on fish: particularly young pike, suckers, grayling and the whitefishes. Young burbot live on plecopterans and chironomids.

Lake trout are the largest of the freshwater fish in the Mackenzie watershed, weighing up to 46 kg (102 lbs) in Lake Athabasca. They are a species of char and, like the Arctic char, much sought-after by sport fishermen. Tourist operators in the North charge $1,000 per week and more for the pleasure of pulling in trophy fish. This sport fishery centers on Great Bear and Great Slave lakes.

Lake trout grow very slowly and have life spans of up to 60 years. Adult lake trout spawn in alternate years or, in some cases, every third year. Due to extreme conditions of climate and limited food, the nothern lakes support limited populations of old (greater than ten years), large trout. Because of slow growth rate and late age of maturity, overfishing is a distinct threat to these deep-swimming denizens of the cold northern lakes.

The downstream sections of the Mackenzie near the Delta are important as a migration route for anadromous species such as Arctic char, cisco, inconnu, broad and humpback whitefish. Delta lakes and channels are also important as feeding, rearing and overwintering areas. The whitefish and cisco are the more abundant and are caught extensively by the native fishermen of the Delta region. Also found in the Delta are anadromous boreal smelt which spawn in the rivers in the spring but spend most of their lives at sea, overwintering in the warmer waters near mouths of rivers.

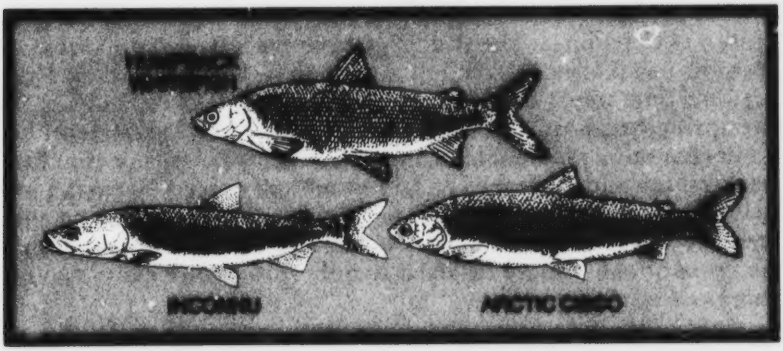
Of the anadromous species, the Arctic char is probably the best known to Canadians. The young are born in fresh water and spend from two to five years growing there before leaving on their first seaward migration. This downstream run of smolts coincides with the spring break-up of river ice; the upstream spawning run by adult char takes place in midsummer and early fall. Arctic char live between ten and 14 years; the largest seldom exceed 60 cm (24 in) in length. (The world record Arctic char was 100 cm/40 in. long and weighed 13 kg/29 lb) They reach sexual maturity between four and six years of age but are believed to only spawn once every two or three years.



Arctic char

Arctic char and Arctic cisco are highly valued by the Inuit of the Delta and coastal regions. There are three ciscos: Arctic, least and lake. Arctic cisco grow faster and live longer than do the other cisco species. While Arctic cisco attain lengths of 60 cm (24 in), the smaller two seldom reach 40 cm (16 in). Both Arctic and least cisco migrate downstream in the spring to feed in the Mackenzie estuary. Some lake-dwelling populations of least cisco do not migrate but spend their lives in fresh water. Lake cisco are found in the lakes of the upper Mackenzie basin; they too are non-migratory.

Whitefish, which include inconnu, humpback and broad whitefish, make up the largest portion of the domestic fisheries. Humpback (or lake), and broad whitefish are similar in many respects; both are found predominantly in the Delta area. The broad whitefish, which attain sizes of 60 cm (24 in), are slightly larger than the humpback which average 45 cm (18 in) but can reach over 70 cm (28 in). After being spawned in fresh water, the fry and juveniles of whitefish species live in Delta and nearshore coastal waters.



Inconnu, found throughout the Mackenzie system, are the largest and fastest-growing of the whitefish family. Individuals as large as 15 kg (33 lbs) are routinely caught by native fishermen of the Delta while specimens up to 28.5 kg (63 lbs) have been taken. These great fish can be 1.5 m (5 ft) in length. This species is native to the Northwest Territories, the Yukon and Alaska, but is not found anywhere else on the continent. Biological knowledge of the inconnu is limited but it is known that some populations are anadromous, leaving their feeding grounds in coastal waters near the Mackenzie Delta on their upriver spawning run in summer. They are joined by freshwater populations which accompany them farther upstream to the spawning grounds. After spawning in the late fall, both types of inconnu are believed to return to overwintering habitats closer to the river mouth.

Food fisheries

Fishing is conducted along the Mackenzie from one end of the valley to the other. Native fishermen can be seen netting at the mouths of rivers, in nearby lakes, near settlements and within the Delta. Much of the domestic catch is taken during the fish migrations prior to freeze-up (for fall spawners), and after spring break-up (for spring migrations of species like grayling). The species caught along the river valley and in adjacent streams and lakes include: northern pike, inconnu, least and Arctic cisco, grayling, longnose sucker, burbot, lake trout, broad and humpback whitefish. Exclusive of the fish taken in the Delta, the river harvest is an estimated 250 000 kg (550,000 lb) in some years.

As mentioned, a thriving sport fishery has developed in Great Bear Lake, based on lake trout and grayling. Commercial lodges — open between June and September — are located along the shores of North America's fourth largest lake. Grayling are particularly abundant where the Great Bear River begins its flow toward the Mackenzie. Over the years, fishing pressure has led to a decline in the average size of grayling caught.

Great Slave Lake is only slightly smaller than Great Bear and drains directly into the Mackenzie River. There are at least 25 species of fish in this lake. Over the years, Great Slave has supported a commercial, domestic and sport fishery based on six species: lake whitefish, lake trout, inconnu, northern pike, yellow walleye and grayling. Great Slave Lake has a more extensive drainage basin with major rivers such as the Slave which enters from the south. The lake has deep areas as well as extensive shallows which provide excellent feeding, spawning and overwintering habitat for fish.

The first commercial fishing in Great Slave began in 1945. As part of the management plan set up for this commercial venture, the federal Fisheries Department has continued to monitor fish landings and to conduct test fishing operations. For this reason, more statistical and biological information concerning fish exists for this area than for anywhere else in the Mackenzie Valley. The first season's catches of whitefish and lake trout totalled 700 000 kg (1.6 million lbs). The annual catch peaked at four million kg (nine million lbs) in 1949 before starting to decline. Fishing operations are conducted during summer and winter seasons from the landing points of Wool Bay, Simpson Islands, Hay River and Moraine Bay.

Estuary

A hundred thousand years ago, during the last stages of the Pleistocene Ice Age, much of the world's sea water was locked up in continental ice sheets. Because of this, the surface of the global ocean was 150 m (500 ft) lower than it is today. What are now the continental shelves were then broad coastal plains. As the ice slowly melted, the ocean level rose at a rate of about one metre per century, flooding these plains and inundating valleys that had been cut out by major rivers. Old estuaries disappeared under the sea and new ones were formed. (The polar ice caps are still melting but at a rate of less than a metre every thousand years.)

The estuaries of the world's great rivers vary in form, depending on the volumes of sediment washed down, and/or the amount of nearby coastal erosion. In locations where river flow and silt loading is high, the ancient valleys have been filled in and some have continued to build outward into deltas. As a general rule, deltas are more likely to form in coastal areas where the tidal ranges are small and where sea currents cannot easily redistribute the sediment brought down by the river. The world's largest deltas are associated with rivers that have high seasonal discharges. The channels of a delta are usually shallow with the shallowest part being a sand bar at the mouth of each channel.

The physical/chemical nature of estuaries is strongly influenced by the size, climate, geology and vegetation of its watershed. The most significant freshwater contribution to the Beaufort Sea is the Mackenzie River. Other sources, such as the Babbage and Firth rivers are, by comparison, minor; influencing only the immediate area of their discharge. Significant physical processes in an estuary include erosion, transport of sediment, and deposition: phenomena which are reversible and vary with the strength of the current.

At the mouth of the Mackenzie, sediments carried downstream have accumulated to form a maze of alluvial banks and islands interspersed with innumerable lakes and channels. This is the Mackenzie Delta. It extends from the eastern edge of the

Richardson Mountains to the Caribou Hills east of Richards Island (Figure 6). The coastline here is complex and ever-changing, constantly being altered by erosion and the redeposition of materials. Several large channels carry Mackenzie River water through the Delta into the Beaufort Sea.

Hydrographic studies made in conjunction with the Beaufort Sea Project have shown that about a third of the total river flow moves into Kugmallit Bay through the East Channel, on the east side of Richards Island. A quarter of the river's discharge follows the west shore of Richards Island into Mackenzie Bay while the remainder moves westward into Shallow Bay (an arm of Mackenzie Bay). The rate of Mackenzie River outflow is markedly seasonal, with peak freshet in June exceeding 20 000 cubic metres per second (m^3/sec). In the depths of winter the flow rate slows to about 4 000 m^3/sec.

Estuaries are regions of variability and extremes, and any plant or animal living there must be adaptable. Because estuaries are relatively shallow, they are more affected by fluctuations in wind and temperature than is the open ocean. In the estuarine progression from river to ocean, a salinity range of zero parts per thousand ($^0/oo$) to 30 $^0/oo$ or more is common. Temperature gradients are fairly predictable: in summer, the surface water is warmer than the water at depth; in winter this gradient is reversed. In the southern Beaufort Sea, however, additional complicating factors are involved. The Mackenzie estuary is warmed by 24 hours of sunlight in summer and lies under a sheet of covering ice in winter; warm river waters mix with cold offshore waters upwelling from the bottom. Compared to estuaries in more temperate regions, tidal fluctuations are minimal.

The Mackenzie estuary is basically a two-layered circulation system resulting from the intrusion of a wedge of denser salt water beneath lighter and less saline water originating in the river. Near-surface water continues in a downstream direction whereas water near the bottom moves toward the shore. Tidal and wind-induced currents modify this density stratification pattern by imposing vertical mixing. This stratified system carries surface organisms and nutrient salts downriver to the sea and those in the offshore bottom water toward the inner Delta, often from below the nutrient-depleted euphotic zone (near sea-surface where photosynthesis takes place). The estuarine waters, as a result, are generally richer in nutrient salts than either the offshore waters or the river.

The distance fresh water travels from the Delta outward before mixing with salt water (hence delineating the estuary), is dependent on several factors. One of these is the Coriolis effect, common to all estuaries of the northern hemisphere. The force of the earth's rotation deflects flowing surface water to the right; that is, eastward in the Beaufort Sea. This is the reason for the slightly lower salinities to be found along the Tuktoyaktuk Peninsula east of the Mackenzie Delta. The distance northward that fresh water from the Mackenzie penetrates into the sea depends on the river's flow rate, the prevailing ice conditions, winds and currents.

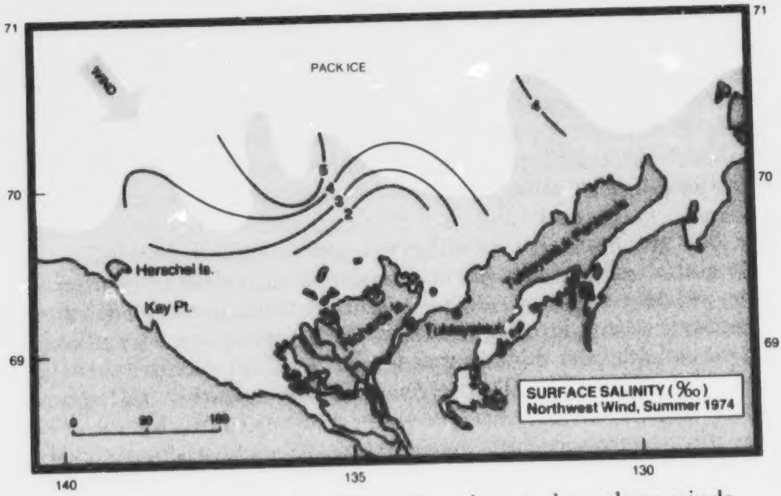
Several methods have been used to follow and study the materials discharged by the Mackenzie River into the Beaufort Sea. The relatively warm water and high sediment load carried downstream and into the southern Beaufort appears as a colored plume which can be observed and photographed from both aircraft and satellite (Figure 5). It is this turbidity and warmth which helps to identify surface water as being of Mackenzie origin. The plume often extends up to 70 km (45 mi) from shore, veering to the east and forming a band 35 km (22 mi) wide. It is seldom deeper than ten metres (33 ft.) below the surface.

A second tracking technique is by salinity measurement. Wide fluctuations in salinity occur both annually and seasonally. Salinity generally increases both with depth and with distance from the freshwater source. Low salinity values are to be found farther out from shore during the freshet period. Figure 9 shows the differences in surface salinity under varying conditions. (However, the inflow of river water, wind and tide may combine to disrupt such salinity stratifications.)

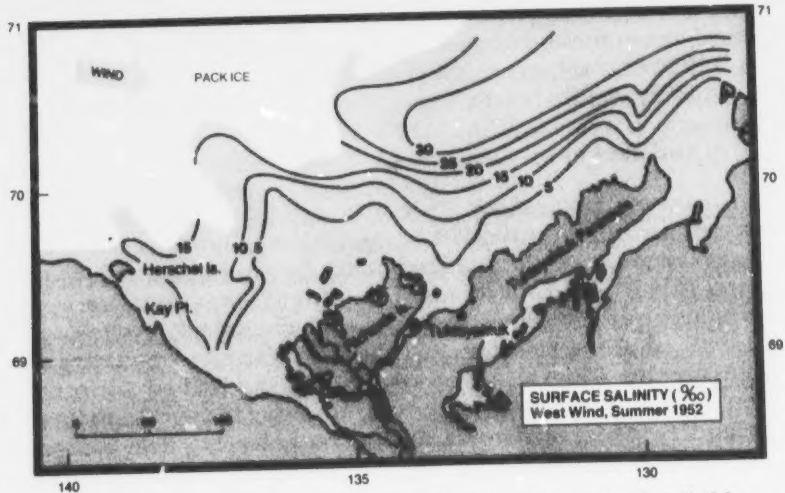
Tides and surges

Tides at Tuktoyaktuk seldom exceed 0.5 m (20 in) and tidal currents are minor in the Mackenzie estuary. But storm tides and surges can increase the sea level water height by as much as two metres (6½ ft) and an increase of one metre is not uncommon. (A storm surge is a sudden storm-induced rise in sea level along a gradually shelving coastline.) In the south Beaufort Sea they are most common when strong northwesterly winds blow during the open water season. The water piles up ahead of the wind and floods the land. Evidence of abnormally high water levels is demonstrated by driftwood stranded far behind the beaches (Page 29). Vast areas of low-lying coastal lands are flooded. Loss of human life due to storm surges has been reported and now with increased coastal development, the problem must be recognized in engineering designs and during operations.

Large areas of salt marsh are often found in close ecological relationship with estuaries. This is the case with the mouth of the

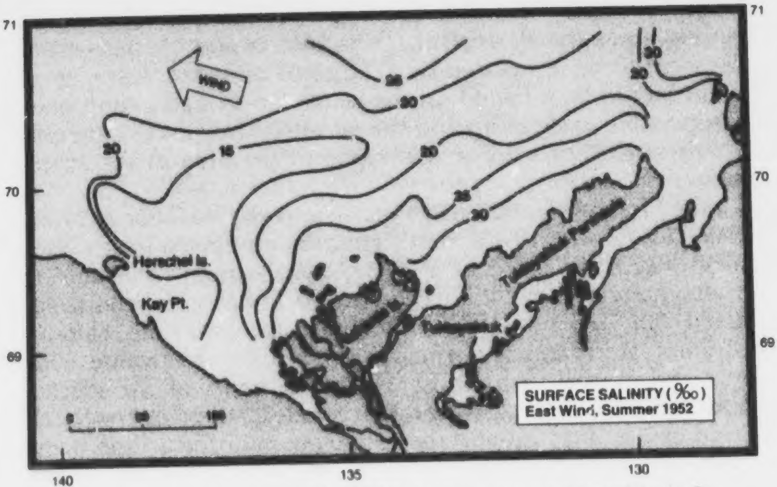

71
71
WIND
PACK ICE
5
4
3
2
70
70
Herschel Is.
Kay Pt.
Tuktoyaktuk
69
69
SURFACE SALINITY (‰)
Northwest Wind, Summer 1974
0
50
100
140
135
130

A: After an extended period of northwesterly onshore winds the southern Beaufort Sea is characterized by waters of low salinity; the fresh river water is held close to shore by the wind and pack ice.

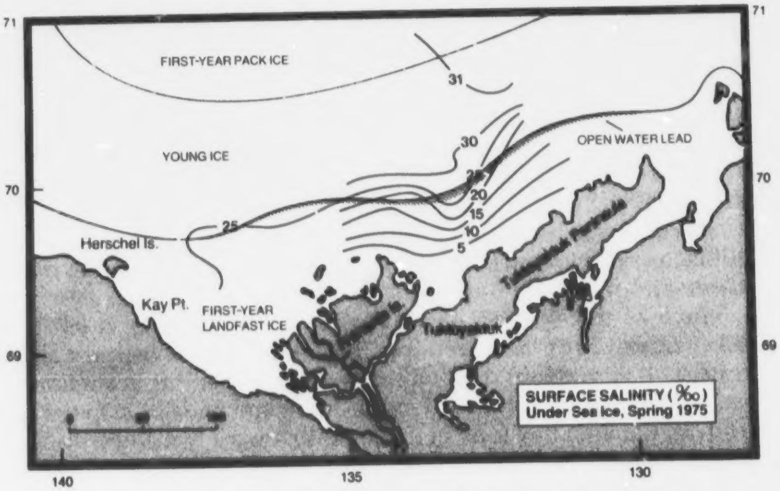

71
71
WIND
PACK ICE
30
25
20
15
10
5
70
70
15
10
5
Herschel Is.
Kay Pt.
Tuktoyaktuk
69
69
SURFACE SALINITY (‰)
West Wind, Summer 1952
140
135
130

B: In summer of 1952 westerly winds resulted in high salinities. A decrease in salinity near the ice pack is believed due to the influence of melt waters.

Figure 9(A-D): Differences in surface salinity under varying conditions.


WIND
Herschel Is.
Kay Pt.
Tuktoyaktuk Peninsula
Tuktoyaktuk
SURFACE SALINITY (‰)
East Wind, Summer 1952
71
70
69
140
135
130

C: Upwelling occurred in 1952 during strong easterly winds. Fresh surface water was transported offshore and in its place, deeper more saline water moved inward and upward, resulting in higher salinities near shore.


FIRST-YEAR PACK ICE
YOUNG ICE
OPEN WATER LEAD
31
30
25
20
15
10
5
25
Herschel Is.
Kay Pt.
FIRST-YEAR LANDFAST ICE
Tuktoyaktuk Peninsula
Tuktoyaktuk
SURFACE SALINITY (‰)
Under Sea Ice, Spring 1975
71
70
69
140
135
130

D: The effects of wind are nullified below sea ice and the emergent fresh Mackenzie water is distributed primarily under the influence of horizontal pressure differences and the Coriolis force.

Mackenzie where wide salt flats provide feeding, staging and breeding areas for shorebirds, geese and swans. If these critical areas were to be inundated by a surge of oil-laden water, severe damage would be inflicted on the birds. Oil-soaked marsh plants are impossible to clean up and the oil would remain as a threat to birds or any other wildlife that came to the area in subsequent years.

Many freshwater species of plants and animals cannot survive a flood of salt water. Freshwater animals, immersed in sea water, tend to lose body fluids in a physiological attempt to dilute the overall salinity. If they cannot return to fresh water, the animals are stressed and, depending upon their tolerance, may die. Salt- and freshwater fluctuations normal to an estuary determine which plants and animals inhabit it. Tolerance limits of the resident species must be broad. Nonresident species, either of fresh or of marine origin, may inhabit the estuarine area for a time if they possess the mobility to move back into their preferred environment.

Plant growth

Estuarine plant life depends on favorable conditions of nutrients, sufficient light, water temperature and salinity. For plants that attach to the bottom, a suitable substrate is also required. Sessile plants such as kelp require a rocky surface onto which the seaweed's grasping organ, or "holdfast" can attach. In the absence of strong currents and/or wave action, the size of the anchor rocks is less crucial. Divers exploring the kelp forests of world oceans where the broad-fronded plants grow upward from depths of ten fathoms (60 ft) or more have observed small stones completely enveloped in the holdfasts of older plants. With time, the entire holdfast may become buried by sediment, giving it additional anchorage.

Much of the western Arctic Ocean is underlain by mud; the Mackenzie estuary is no exception. Such areas do not support algal forests such as are found along temperate shores but in sheltered locations where a rocky seabed exists, luxuriant beds of kelp can be found. In Balaena Bay (one of the areas extensively studied during the Beaufort Sea Project), a shingle beach slopes to a rocky bottom in a narrow inlet of the bay. Marine plant life here varies from microalgae to kelp (Table B).

Lack of sufficient light for photosynthesis is a major limiting factor to marine plant growth in the Mackenzie estuary. During the winter, ice and snow diminish the amount of light that can reach the water. Some plant forms are adapted to lower light intensities

Table B
Algal zonation in Balaena Bay, Cape Parry (from NORCOR 1975)

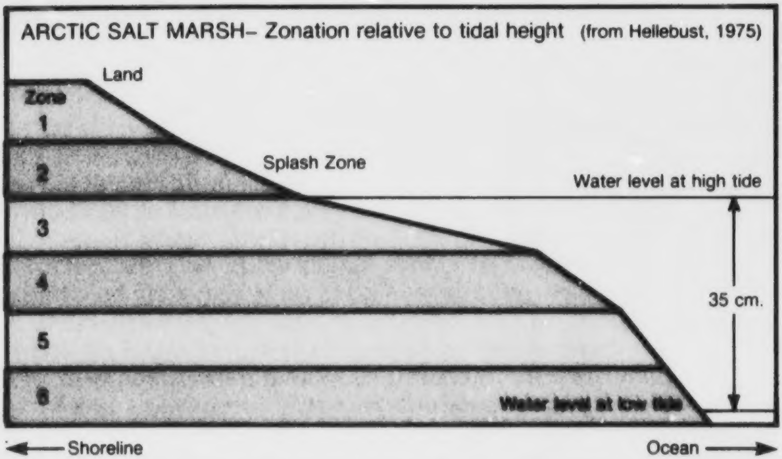
Zone	Tidal Height	Species
1 (Upper shingle)	high tide to 2 m depth	*Calothrix scopulorum* (nitrogen-fixing blue-green algae) *Oscillatoria* spp. (blue-green filaments) *Chrococcus* sp. (blue-green coccoid) Pennate diatoms *Protoderma marinum* (dominant green algae on shaded side of shingles) *Sphacelaria arctica* (dominant filaments - brown algae) *Pylaiella littoralis* (filaments - brown algae) *Ralfsia fungiformis* (crustose brown algae)
2 (Lower shingle - cobble)	2 to 4 m depth	*Fucus distichus* ssp. *evanescens* (dominant brown seaweed) *Chaetomorpha linum* (fine green filaments) *C. melagonium* (coarse green filaments) *Navicula* sp. (diatom) *Melosira sulcata* (centric diatom) *Nitzchia closterium* (pennate diatom) *Sphacelaria arctica* (epiphytic algae)
3 (Mud with scattered cobbles and boulders)	4 to 8 m depth or more	*Fucus distichus* ssp. *evanescens* (dominant brown seaweed) *Desmarestia aculeata* (sub-dominant brown seaweed) *Chaetomorpha melagonium* (dominant green seaweed) *C. linum* (abundant green seaweed) *Sphacelaria arctica* *Laminaria saccharina* (occasional kelp) *Halosaccion ramentaceum* (red tubular seaweed) *Polysiphonia arctica* (branched red seaweed) Pennate diatoms - on seaweeds and mud

▲ Mallik Bay salt marshes. ROGER PERCY

and a progression of under-ice algal blooms can be identified, beginning with the first light of spring. Ice flora have the lowest light requirements and are therefore the earliest to appear. This under-ice flora blooms shortly after the surface snow first melts. When ice break-up begins, phytoplankton deeper in the water column can actively grow. Diatoms are found to be the most abundant plant form in inshore areas, where high nutrient levels, low light intensities and warmer temperatures prevail.

Characteristics of a plant species dictate the amount of light required for growth. Minimum light intensity for photosynthesis in sea ice is about 66 lux (lumen per square metre). In Frobisher Bay planktonic blooms have been recorded at light values of 1000 lux and greater. Summer measurements of subsurface illumination in the region of the Mackenzie River plume have shown that light intensities of 100 lux are rarely reached at a depth of one metre. For this reason, marine biologists believe that active photosynthesis in sediment-clouded plume waters is restricted to the top few centimeters of the water column.

In temperate regions, one of the most biologically productive ecosystems is the salt or tidal marsh, intrinsic to many estuaries. They form on alluvial plains, or in the shelter of spits and islands. Dominated by plants, the species zonation is dictated in part by tidal height and the resultant salinity gradients. In the Arctic, salt marshes are a common though not well-understood feature of the


ARCTIC SALT MARSH– Zonation relative to tidal height (from Hellebust, 1975)
Land
Zone
1
2
3
4
5
6
Splash Zone
Water level at high tide
35 cm.
Water level at low tide
Shoreline
Ocean

ZONE	SUBSTRATE	DOMINANT PLANTS	SUB-DOMINANT PLANTS	DOMINANT ANIMALS
1	Rocks and shingles	Lichens –Caloplaca elegans –Cetraria nivalis –C. cucullata –Thamnolia sp.	Puccinellia andersonii Carex spp. Cochlearia officinalis Salix glauca	
2	Silt-covered by algal mats	Puccinellia phryganodes Wilhelmsia physodes	Sedges –Carex subspathacea –C. ursina Puccinellia andersonii Cochlearia officinalis	
3	Silt-covered by algal mats	Puccinellia phryganodes	Wilhelmsia physodes Cochlearia officinalis Enteromorpha sp.	
4	[illegible]	[illegible]	[illegible]	
5	Mud-covered by algal mat [illegible] Tidal pools	Vaucheria sp. [illegible] Chaetomorpha linum Pennate diatoms Blue greens	Pennate diatoms [illegible] Enteromorpha sp. Rhizoclonium sp. Ulothrix sp.	Nematodes and Protozoans
6	[illegible]	[illegible]	[illegible]	

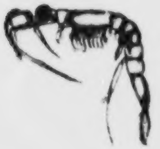
Figure 10

coastline. The plants that grow there form a transitional zone between the tundra and the seaweeds. The marsh plants lead a precarious existence in the narrow band of shoreline bounded by the low tide mark and the splash zone above high tide.

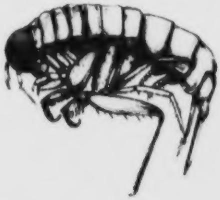
In Balaena Bay, located 300 hundred km (185 mi) east of Tuktoyaktuk, salt marsh vegetation takes up one-quarter of the shoreline. Although sedges and grasses are common inhabitants of salt marshes, in this area they grow only to a height of 35 cm (14 in). Also unusual are the mosses found thriving in places covered at high tide (Figure 10).

Zooplankton

In aquatic food webs, grazing zooplankton are responsible for most of the secondary production. Arctic food chains involving



Zooplankton: Mysid (20 mm)



Parathemisto (30 mm)

W.A.T.E.R. ASSOCIATES LTD.

▲ A coelenterate specimen.

zooplankton can be very short: phytoplankton → zooplankton → seabirds. Some are more complex than this, forming food webs; but within these, the choices can be few. The effect of such trophic relationships is that efficient use is made of a food source. This is of crucial importance in the Arctic, where both primary and secondary production are considered relatively low.

The zooplankton includes representatives of virtually all marine types, either as adults or in the developmental stages. In the Arctic, these organisms often require a full year or more to develop, whereas in temperate waters several generations can be produced in a single year. Zooplankton have the ability to swim up and down in the water column in their search for food. Their larvae normally begin to grow and develop in the food-rich surface layer but, later, sink to depths where food is less abundant.

The populations and distribution of zooplankton in the Mackenzie estuary are greatly influenced by both salinity and temperature regimes, and by the abundance of food. Periodic sampling around the perimeter of the plume yields variable results at different times of year and under differing oceanographic conditions (Table C).

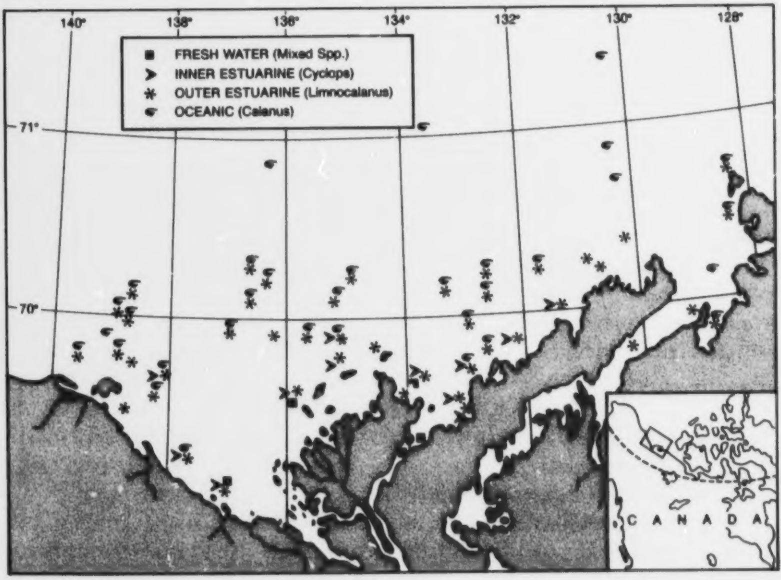

140°
138°
136°
134°
132°
130°
128°
71°
70°
■ FRESH WATER (Mixed Spp.)
➤ INNER ESTUARINE (Cyclops)
✳ OUTER ESTUARINE (Limnocalanus)
◆ OCEANIC (Calanus)
C A N A D A

Figure 11: Known ranges of estuarine zooplankton species.

Table C illustrates the effect of the fluctuations between Mackenzie River outflow and the offshore marine waters, on the species diversity of zooplankton. In 1971, water samples taken were of high salinity and cool - indicative of offshore water having been driven by onshore winds. In 1973 the locations were of lower salinity, warmer, and sampled after a settled period of weather - indicative of the 'no wind case', when the river plume extends north and eastward offshore from the Delta and the Tuktoyaktuk Peninsula.

Table C
Zooplankton species composition off Tuktoyaktuk Peninsula in late July of two years (from Grainger, 1975).

1971	1973
—	*Halitholus cirratus*
Aglantha digitale	—
Aeginopsis laurenti	—
mollusc larvae	—
unidentified annelids	polychaeta larvae
Acartia clausi	*Acartia clausi*
A. longiremis	—
Derjuginia tolli	—
Calanus glacialis	—
Calanus hyperboreus	—
Limnocalanus macrurus	*Limnocalanus macrurus*
Metridia longa	—
Microcalanus pygmaeus	—
Pseudocalanus minutus	*Pseudocalanus minutus*
—	*Eurytemora herdmani*
Oithona similis	—
Oncaea borealis	—
—	*Cyclops* sp.
—	*Cyclopina* sp.
Copepod nauplii	Copepod nauplii
Cirripede larvae	—
—	*Mysis* sp.
—	*Diastylis* sp.
Monoculodes sp.	*Monoculodes* sp.
Eukrohnia hamata	—
unidentified chaetognaths	—
Oikopleura vanhoeffeni	—
21 Total number of species	12

Table D
Zooplankton distribution in the southern Beaufort Sea.

Representative Genera	Origin	Preferred Salinity (parts per thousand)
Daphnia, Diaptomus, Epischura, Bosmina	freshwater	0
Cyclops, Mysis	freshwater and esturine	6
Acartia, Halitholus	estuarine	7 - 20
Limnocalanus, Derjuginia	outer estuarine	25
Aglantha, Calanus	oceanic	20 - 34

Based on their known physiological tolerances, zooplankton can be used as rough indicators of salinity. Those of freshwater origin will be encountered in highest numbers in the fresh river water. As salinity increases, their numbers will decrease. Similarly, oceanic zooplankton will be dominant in more saline waters and decrease in abundance as the salinity decreases. Estuarine species are intermediate in salt tolerance but show preference for specific salt ranges (Table D; Figure 11).

Salinity is only one factor that determines the patterns of zooplankton distribution; feeding habits also exert an influence. For example, *Limnocalanus macrurus*, a plankton feeder, is found at the plume edges where phytoplankton production is greatest.

Zoobenthos

Zoobenthos are those invertebrate animals that live in and upon the sea bottom. They are categorized as "epifauna" when they attach to or crawl along the sea floor and as "infauna" when they live within or burrow into the sediments. Arctic zoobenthos grow more slowly, live longer and reproduce at a slower rate than do their counterparts in warmer oceans. Consequently, the re-establishment of a mature community from a damaged or disturbed state may take over ten years after the damaging event and restoration of the sea floor.

These tiniest of bottom-dwellers are omnivorous feeders, dependent upon a rain of organic detritus from the photoproductive layers of the water column above. However, in the Mackenzie estuary where the photosynthetic input from the surface layers is minimal, their food source is probably transported into the area by either the Mackenzie River or from offshore waters. A second food source, for particulate feeders, is the bacteria and protozoans responsible for decomposition.

The diversity and abundance of a zoobenthos community (Figure 12) depends on such things as predator-prey relationships, seabottom, turbidity, water depth, temperature and salinity. A change in any factor or group of factors may cause an imbalance in the system and result in a reduction or elimination of a population of one species and an increase in yet another. Natural changes in the zoobenthos occur over long periods of time; years rather than seasons. Although everything that regulates the distribution and abundance of zoobenthos is not known, those species that inhabit the silt bottom of the Mackenzie estuary are affected by the river in terms of its great quantities of fresh water and heavy silt loads; the scouring of the sea floor by ice keels, and the variation in food supplies between nearshore and offshore waters.

Some 337 species of benthic invertebrates have been identified in the southern Beaufort Sea. For purposes of description they have been arranged in four zones of distribution and abundance (Figure 13). Closest of these to shore is the Estuarine zone. This zone includes about one-quarter of the Continental Shelf where the mixing of fresh Mackenzie waters with salt marine waters results in low salinities. The number of different species of

Diversity of zoobenthos of the Southern Beaufort Sea (from Wacasey, 1976)

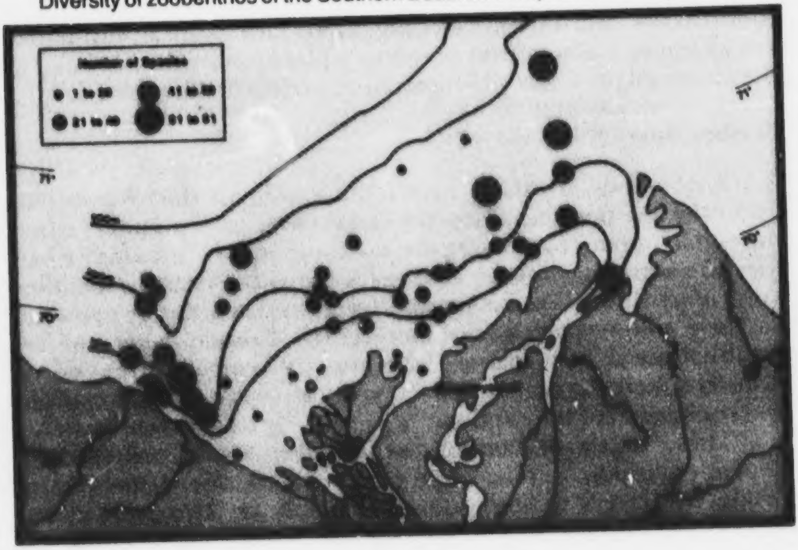
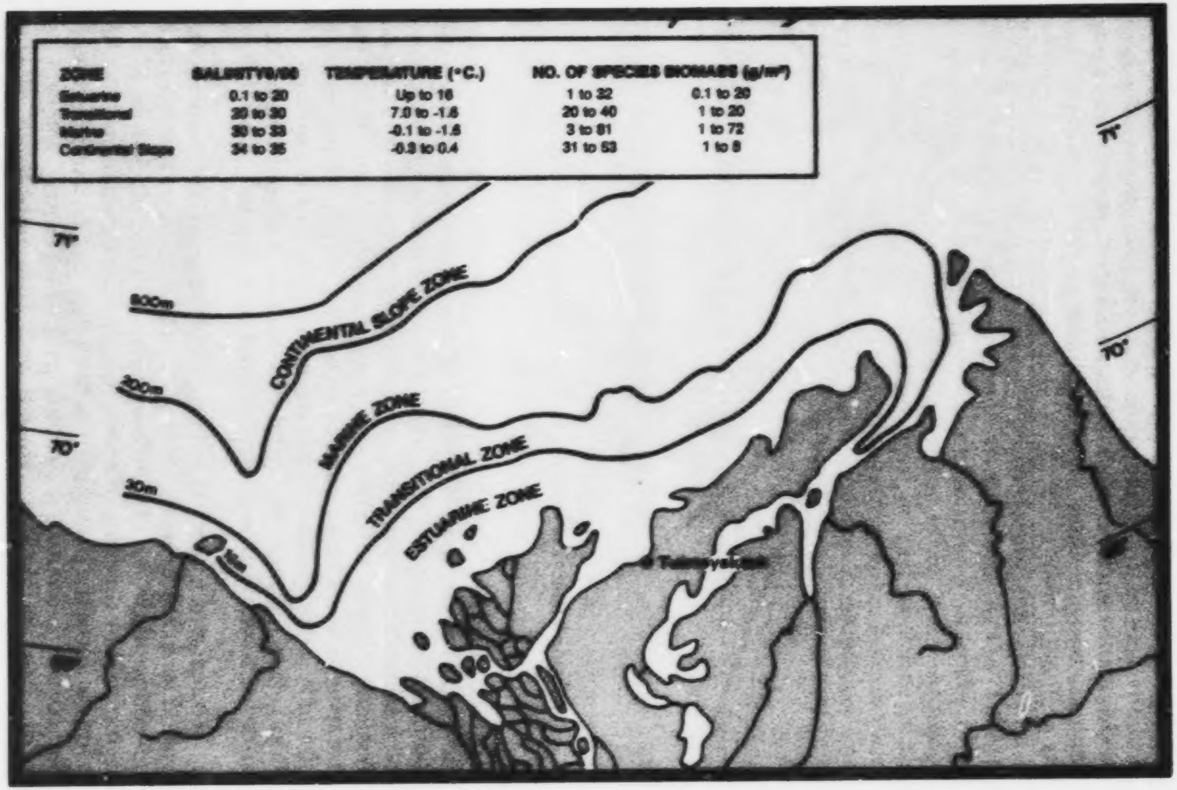


Figure 12

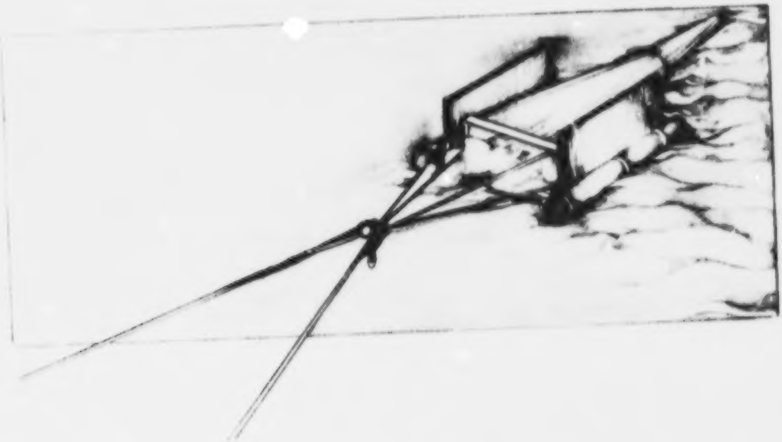


71°
70°
71°
70°
500m
200m
30m
10m
CONTINENTAL SLOPE ZONE
MARINE ZONE
TRANSITIONAL ZONE
ESTUARINE ZONE
Tuktoyaktuk

ZONE	SALINITY0/00	TEMPERATURE (°C.)	NO. OF SPECIES	BIOMASS (g/m²)
Estuarine	0.1 to 20	Up to 16	1 to 32	0.1 to 20
Transitional	20 to 30	7.0 to -1.6	20 to 40	1 to 20
Marine	30 to 33	-0.1 to -1.6	3 to 81	1 to 72
Continental Slope	34 to 35	-0.3 to 0.4	31 to 53	1 to 8

Figure 13: Zoobenthic zones hypothesized by Wacasey (1976).

zoobenthos found here is extremely low, a result of the intolerance of many species to extended periods of low salinity. Unstable conditions — such as high sedimentation, frequent ice scour,

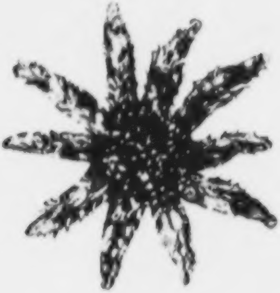


Epibenthic sled sampler being towed along sea bottom.

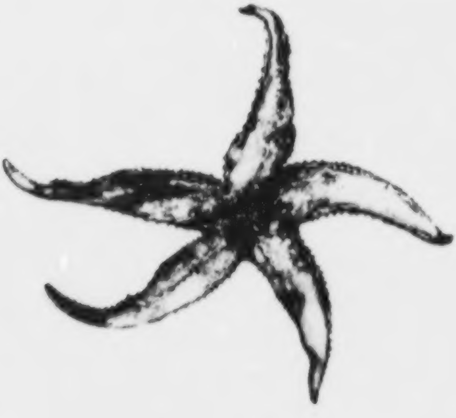
currents and fluctuating nutrient supply — create a habitat tolerated by fewer than 20 species of benthic animals. Among the dominant forms are the crustaceans *Onisimus glacialis* and *Boeckosimus affinis*, the mud clam *Yoldiella intermedia* and isopod *Mesidotea entomon*. Starfish are conspicuously absent from the Estuarine zone. The average biomass (dry weight of the animals collected) is two grams per square metre (g/m^2) of sea bottom. In Mason Bay, a protected and productive embayment in the Estuarine zone, the biomass values approach 20 g/m^2.

To seaward is the Transitional zone, "transition" because the water temperatures and salinity fluctuate widely at the interface between wind-driven offshore seawater and the Mackenzie River discharge. The diversity of zoobenthic species varies from 20 to 40, an indication of the presence of both marine and estuarine animals. The species inhabiting this zone are, of necessity, tolerant of fluctuations in their surroundings. Two polychaete worms *(Artacama proboscidea* and *Trochocaeta carica)*, and a species of clam *(Portlandia arctica)*, are of this category. Combined, they add significantly to the total biomass which averages five g/m^2. Bottom scouring by ice keels results in the elimination of invertebrates in localized areas, particularly in waters from 20 to 40 m (65 - 130 ft) deep, where frequency of ice scouring is high.

These first two benthic zones comprise the Mackenzie estuary and its plume of slowly sinking silt and sand. Beyond this, and encompassing more than a half of the Continental Shelf, is the Marine zone. The waters here are much deeper, the salinity fairly stable at 30 ⁰/oo, and the temperature varies little (-0.1 to -1.58°C). More interesting is the diversity and numbers of zoobenthos, probably greater here than in any of the other zones. Although the average biomass is about 14 g/m^2, a rich area near Cape Dalhousie has 81 species of benthos, covering the sea bottom with a density of 71 g/m^2. (The word "rich" requires qualification since



Solaster papposus

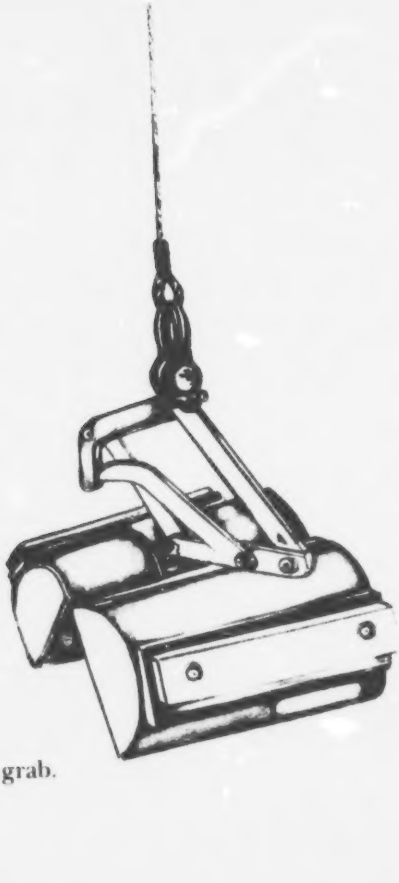


Icasterias panopla

values are lower in the Beaufort Sea than in eastern Arctic waters by a factor of approximately two.) Thirteen representative species are polychaete worms, starfish and clams.

The Continental Slope zone is the deepest and farthest offshore. The benthic community is distinguished by the presence of eight species that are absent or rare elsewhere on the Shelf. Most are mud-dwelling organisms such as worms and clams, found in waters from 1 000 to 2 000 m (3,300-6,600 ft) deep. The average biomass of this zone is 4 g/m^2, and more than 20 species have been recorded in dredge and grab collections. Since the environment is stable — no ice scouring, and uniform temperature and salinity — the availability of food appears to regulate the zoobenthos.

It is important to emphasize that this information deals only with the infauna. Larger invertebrates which live on the surface of the sea floor such as isopods, brittle stars, sea stars, gastropods and



Benthic "clam" grab.

other epifauna are not usually taken by standard sampling techniques such as bottom grab. For this reason the submersible *Pisces IV* was deployed on a number of dives in the vicinity of Herschel Island in 1974 and 1975. Visual observations from the submarine revealed an extremely patchy distribution and we can conclude that such organisms do not contribute substantially to the biomass of the faunal zones discussed above. This study has also shown that at least 30 percent of the Transition zone is affected by ice scouring and that, within scour troughs, the abundance of the epifauna is considerably reduced compared to surrounding areas.

Patchiness in biological distributions is a common phenomenon and one which must be considered in the design of sampling and/or monitoring programs. Aggregates of animals or plants form in response to the satisfaction of a definite need: physical, chemical or biological. Definitions of the factor(s) responsible for such a patch or clump can be simple or complex. Prior to setting up a monitoring program for the individuals or species present, it is necessary to define the extent of the patch, why it is where it is and when it exists (if it is transitory or seasonal).

The study of a benthic community is very labor intensive due to the small "bites" of information derived from each grab or dredge sample. However, from this baseline data, sensitive areas and species can be better delineated. The richest known areas of

Biomass of zoobenthos of the Southern Beaufort Sea (from Wacasey, 1976)

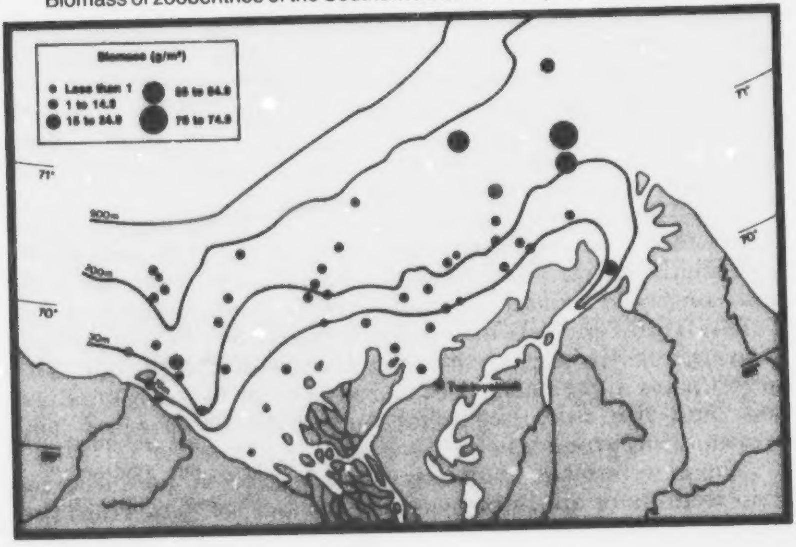


Figure 14

the south Beaufort Sea with respect to bottom fauna (highest biomass) are protected embayments such as Mason Bay and the eastern part of the Marine zone (Figure 14).

Fishes

In the southern Beaufort Sea, anadromous species such as Arctic char, inconnu and whitefish represent a substantial and, in terms of the domestic fishery, important component of nearshore stocks. At least seven anadromous species — those fish obliged to return from the sea to spawn and/or overwinter in fresh water — have been recorded in the region. It is interesting to note that several fish, lake trout and whitefish for example, which are typically freshwater inhabitants in temperate areas, often migrate into estuarine waters in the Arctic to feed.

The area of greatest species diversity is the Mackenzie Delta and estuary. This is attributable to the area's complement of freshwater, anadromous and, to a lesser extent, marine fishes. Currently-available life history information for the more abundant of the 26 fish species captured in the outer Mackenzie Delta region (Table E) is summarized in Table F. The marine fishes, including the Arctic flounder, Arctic cod and fourhorn sculpin, are also found in this nearshore brackish zone as well as in isolated pockets of salt water in Tuktoyaktuk harbor and along the northern coasts of Richards Island, most notably in Mason Bay and Mallik Bay. These areas also contain substantial numbers of whitefish, cisco and inconnu throughout the summer months. The western portion of Shallow Bay is a sensitive migration corridor for Arctic char, inconnu and cisco in late summer and fall. The Delta is important as a nursery ground for young fish; not only for resident species such as burbot and northern pike, but also for anadromous fishes such as Arctic char, Arctic and least cisco.

The number of species and abundance of fish declines significantly as one moves from the mouth of the Mackenzie River, both out to sea and along the shore. Boreal smelt, Arctic and least cisco comprised about 90 percent of the test catch along the north Tuktoyaktuk Peninsula during the Beaufort Sea Project. Within Tuktoyaktuk harbor, Arctic cisco dominated the catches. The largest hauls in the nearshore zone were made as freeze-up drew near and fish were beginning to migrate to spawning and overwintering grounds in fresh water.

Smelt were taken at all depths in the water column whereas cisco were more apt to be caught in surface set nets. Fourhorn sculpins, also taken in this area, were found to be most numerous in bottom sets. Biologists feel that these life habits represent an

Table E
Common occurence of fishes in the nearshore Beaufort Sea.

Species		Delta Area	Yukon Coast
● Pale eelpont	*Lycodes pallidus*	X	
◆ Trout perch	*Percopsis omiscomaycus*	X	
◆ Pond smelt	*Hypomesus olidus*	X	
■ Arctic lamprey	*Lampetra japonica*	X	
◆ Lake chub	*Couesius plumbeus*	X	
◆ Spoonhead sculpin	*Cottus ricei*	X	
◆ Lake trout	*Salvelinus namaycush*	X	
◆ Longnose sucker	*Catostomus catostomus*	X	
◆ Northern pike	*Esox lucius*	X	
◆ Burbot	*Lota lota*	X	X
● Starry flounder	*Platichthys stellatus*	X	X
● Pacific herring	*Clupea harengus pallasi*	X	X
● Saffron cod	*Eleginus navaga*	X	X
■ Inconnu	*Stenodus leucichthys*	X	X
■ Rainbow smelt	*Osmerus mordax*	X	X
● Arctic cod	*Boreogadus saida*	X	X
■ Humpback whitefish	*Coregonus clupeaformis*	X	X
◆ Round whitefish	*Prosopium cylindraceum*	X	X
■ Broad whitefish	*Coregonus nasus*	X	X
● ◆ Ninespine stickleback	*Pungitius pungitius*	X	
◆ Arctic grayling	*Thymallus arcticus*	X	
● Arctic flounder	*Liopsetta glacialis*	X	X
● Fourhorn sculpin	*Myoxocephalus quadricornis*	X	X
■ Least cisco	*Coregonus sardinella*	X	X
■ Arctic cisco	*Coregonus autumnalis*	X	X
■ Arctic char	*Salvelinus alpinus*	X	X
	Totals	26	15

- ● marine species
- ◆ freshwater species
- ■ anadromous species

Table F

Summary of information presently available on the life history of the most anadromous and marine fish species utilizing the outer Mackenzie Delta. (Modified from Percy, 1976).

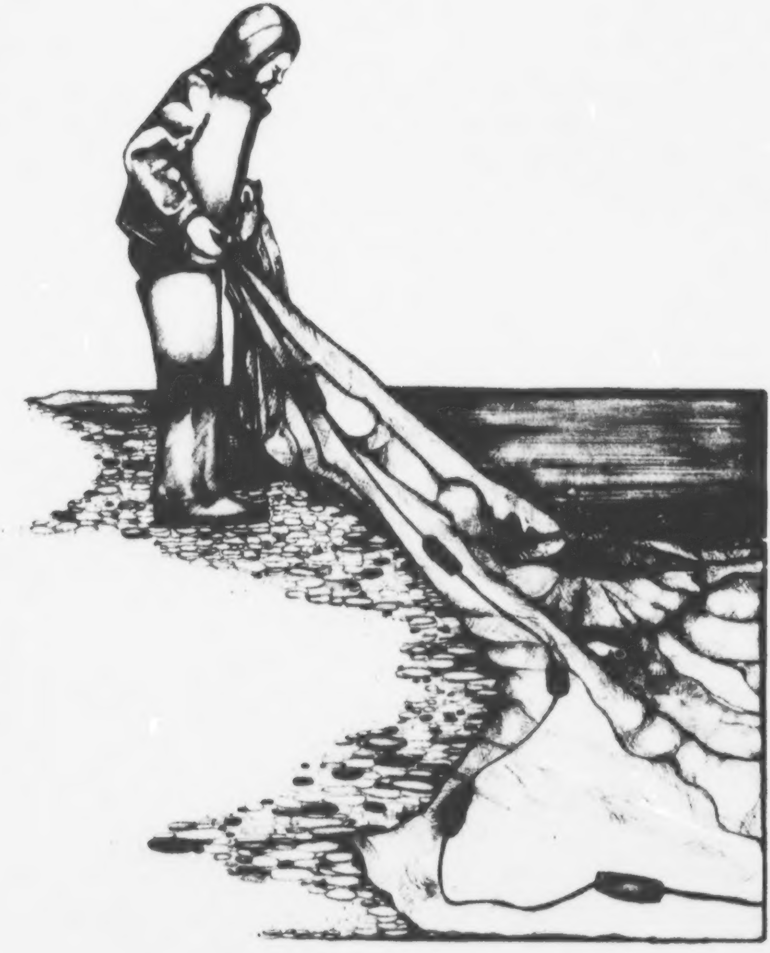
Anadromous Species	Maximum Age in Outer Delta	Age at Maturity	Spawning Season	Spawning Grounds Known (K) and Suspected (S)	Spawning Habitat	Prespawning Migration	Postspawning Migration	Overwintering in Outer Delta
Arctic cisco	11 (11▲)	7	late Fall	Tributaries Arctic Red and Peel R. (K)	over gravel	throughout summer	early October	yes
Arctic char		4 - 5*	late Fall	Cache and Fish Ck. (K)	pools or riffles over gravel	mid-August until late September	at breakup	mountain streams not delta
Boreal smelt	8*	6*	early Spring	Arctic Red R. area & Holmes Ck. (S)	gravel substrate	prior to breakup	June - early July	along coast
Broad whitefish	15	3 - 4	Fall	Arctic Red R. and main Mackenzie R. (K)	small lakes & Mackenzie backeddies	early Fall	November	yes
Humpback whitefish	18	7	Fall	Arctic Red. R., main Mackenzie & tributaries (K)	stone or hard silt substrate	late summer	October - November	yes
Least cisco	11	5	late Fall	upper Mackenzie R. tributaries (S)	sand or gravel substrate	mid-August until after freeze-up	unknown	yes
Inconnu	16 (22▲)	6	Fall	tributaries of Peel, Arctic Red & Mackenzie R. (S)	swift water over coarse gravel	summer	October	yes
Arctic flounder	12*	5*	Winter	Mallik Bay & northeast coast Richards Is. (S)	probably silt substrate	localized	—	yes
Fourhorn sculpin	14*	3*	Winter	Mason & Mallik bays (S)	probably sand substrate	relatively localized	—	yes
Pacific herring	(14▲)	(6▲)	Spring	Northeast coast Richards Is. (S)	nearshore in shallows	unknown	—	yes
Saffron cod	16*	unknown	unknown	none	breed at sea	unknown	—	yes
Starry flounder	15*	unknown	Winter	none	shallows at river mouths	localized	—	yes

* Otolith based ages; other ages are calculated from scales.

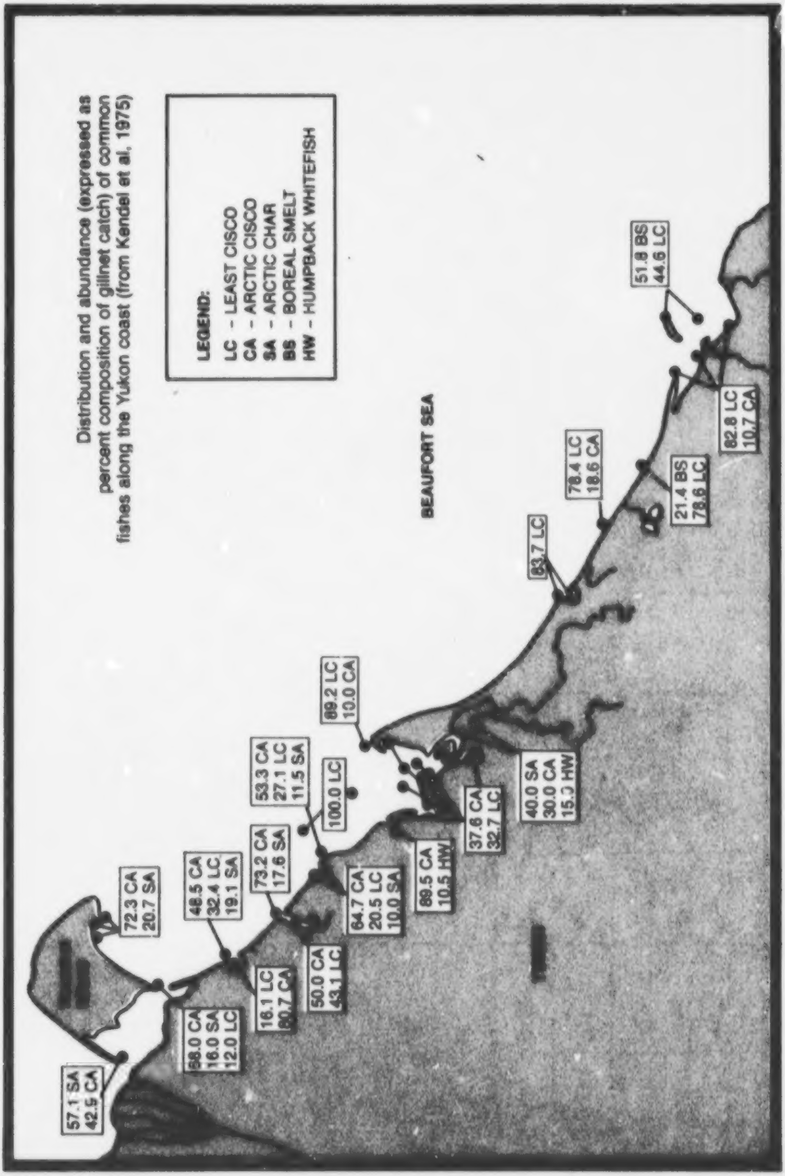
▲ Ages reported from elsewhere in Delta.

important behavioral adaptation, allowing greater utilization of available habitat.

Arctic and least cisco, Arctic char, humpback whitefish (all anadromous species), and the marine fourhorn sculpin comprised 95 percent of the summer test catches along the Yukon coast (Figure 15). Smaller numbers of boreal smelt, inconnu and Arctic flounder were also found there. Annual variations in the abundance and distribution of species in the nearshore areas could be dramatic.



Beach seining.



Distribution and abundance (expressed as percent composition of gillnet catch) of common fishes along the Yukon coast (from Kendel et al, 1975)

LEGEND:
LC - LEAST CISCO
CA - ARCTIC CISCO
SA - ARCTIC CHAR
BS - BOREAL SMELT
HW - HUMPBACK WHITEFISH
BEAUFORT SEA
57.1 SA 42.5 CA
72.3 CA 20.7 SA
58.0 CA 16.0 SA 12.0 LC
48.5 CA 32.4 LC 19.1 SA
16.1 LC 80.7 CA
73.2 CA 17.6 SA
50.0 CA 43.1 LC
53.3 CA 27.1 LC 11.5 SA
64.7 CA 20.5 LC 10.0 SA
100.0 LC
89.5 CA 10.5 HW
89.2 LC 10.0 CA
37.6 CA 32.7 LC
40.0 SA 30.0 CA 15.0 HW
83.7 LC
78.4 LC 18.6 CA
21.4 BS 78.6 LC
82.8 LC 10.7 CA
51.8 BS 44.6 LC

Figure 15

Many of the anadromous fish netted as far away as Herschel Island or to the east along Tuktoyaktuk Peninsula are members of the Mackenzie breeding stock. Many of them migrate into the Delta in late summer and early fall. An exception to this is the boreal smelt, a fish that moves up the Mackenzie River to spawn in tributary streams prior to ice break-up in early spring and returns to the sea by early summer.

Fish tagging studies underway since 1972 have confirmed large-scale migration patterns. For example, Arctic cisco marked and released near Herschel Island have been recaptured at Shingle Point at the edge of the Mackenzie Delta. Others tagged along the coast have been taken by domestic fishermen at the head of the Delta at Aklavik and Arctic Red River; still others marked and released near Arctic Red River were caught not long afterward 300 km (185 mi) farther upstream near Fort Good Hope.

Within the study area, Arctic cisco utilize only the Mackenzie River system for spawning and overwintering. Starting in July they migrate south as far as Great Bear River. Spawning takes place in the late fall and early winter. Non-spawning individuals, and those that have spawned, return downstream to the Delta area. With them go fry to the lower reaches of the river where they remain in fresh or brackish coastal waters for several years. Arctic cisco mature in about seven years; their diet consists largely of insects and crustaceans (Figure 16). Like most other migrant species, they do not feed while on their spawning run.

Least cisco are found throughout the Mackenzie drainage system and dispersed along the Yukon coast and Tuktoyaktuk Peninsula. Although many were tagged, relatively few have been recaptured. This might be due either to high mortalities and stress associated with the capture/tag procedure or the ability of the fish to avoid the nets of the domestic fishery. Only potential spawners appear to migrate to the breeding grounds in the inner Delta. These fish are found moving upstream between August and freeze-up. Freshwater least cisco follow seasonal migration paths within the lake/stream systems along the Beaufort Sea coast, much as the anadromous varieties do.

Broad whitefish are of particular value to residents of the north and are subject to both domestic and commercial fishing. They are common throughout the lower Mackenzie from Fort Simpson to the Delta where they are found in their greatest numbers. The annual upstream spawning migration of broad whitefish takes place in September and October. Spawned-out fish have been seen in late October both at the mouth of the Arctic Red River and in the main channel of the Delta. The fish return

The diets of the Arctic Cisco, an opportunistic feeding fish, and the Fourhorn Sculpin, a specialist (from Kendel et al. 1975)

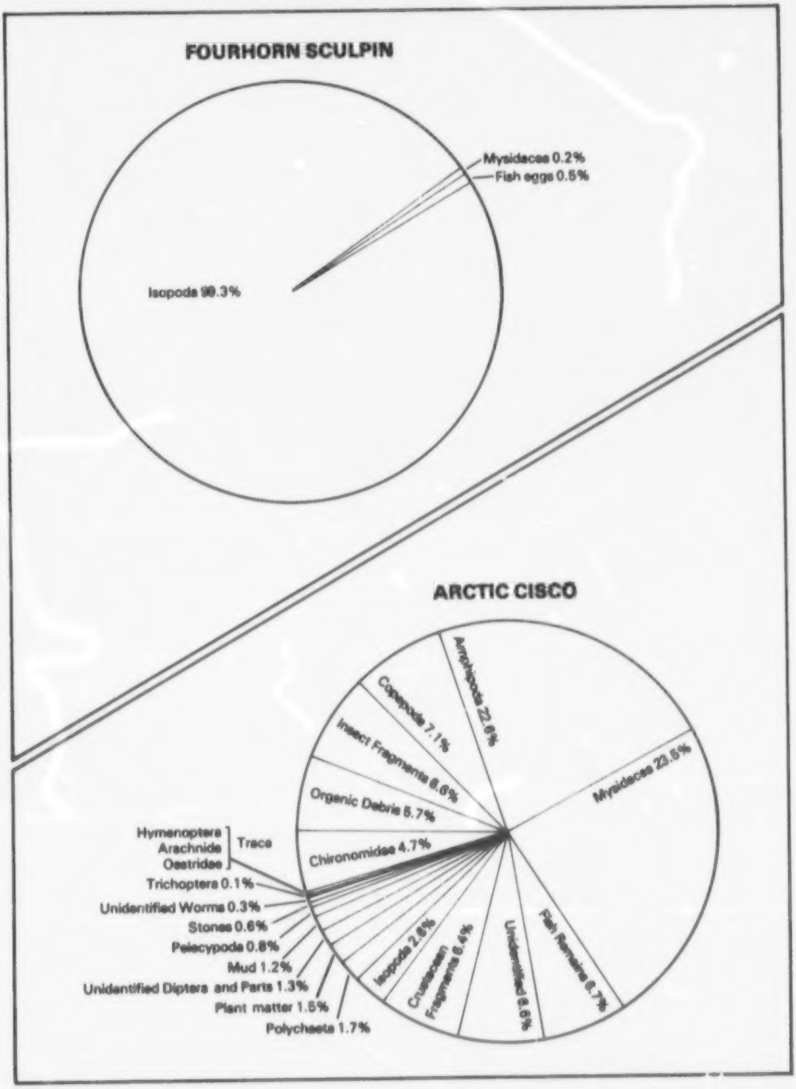
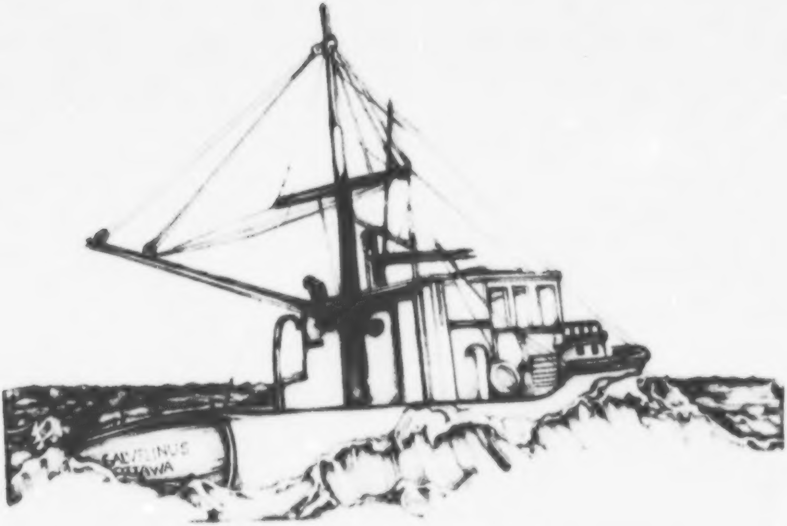


Figure 16



Research vessel *Salvelinus.*

downstream in early November. The diet of broad whitefish includes gastropods, trichopterans and plant detritus.

Humpback whitefish share the same distribution patterns, migration routes and spawning areas as the broad whitefish but are more numerous. Tag recovery data indicates they migrate upstream through the system at least as far as Arctic Red River. They live longer and mature later than do broad whitefish. The age of fish can be estimated from laboratory examination of fin or scale samples which can be taken during tagging operations. Another method involves the dissection of the otoliths (inner ear bones) of dead fish. The diet of humpback whitefish is similar to that of broad whitefish (Figure 17). Lake-caught specimens appear to have a wider variety of food sources than do coastal-dwellers.

Arctic char, another species important in the domestic fishery, is found in North Slope drainages such as the Firth and Babbage rivers as well as the Mackenzie. Spawners leaving the sea for breeding grounds in the upper Mackenzie pass through the western part of the Delta through West, Peel and Husky channels. Two anadromous populations of Arctic char have been identified in the Delta region; one of these spawns in Fish Creek, a tributary of the Rat River, while the other uses Cache Creek, which drains into Big Fish River.

Anadromous char disperse widely along the Beaufort coast during the spring and summer. Those that are due to spawn

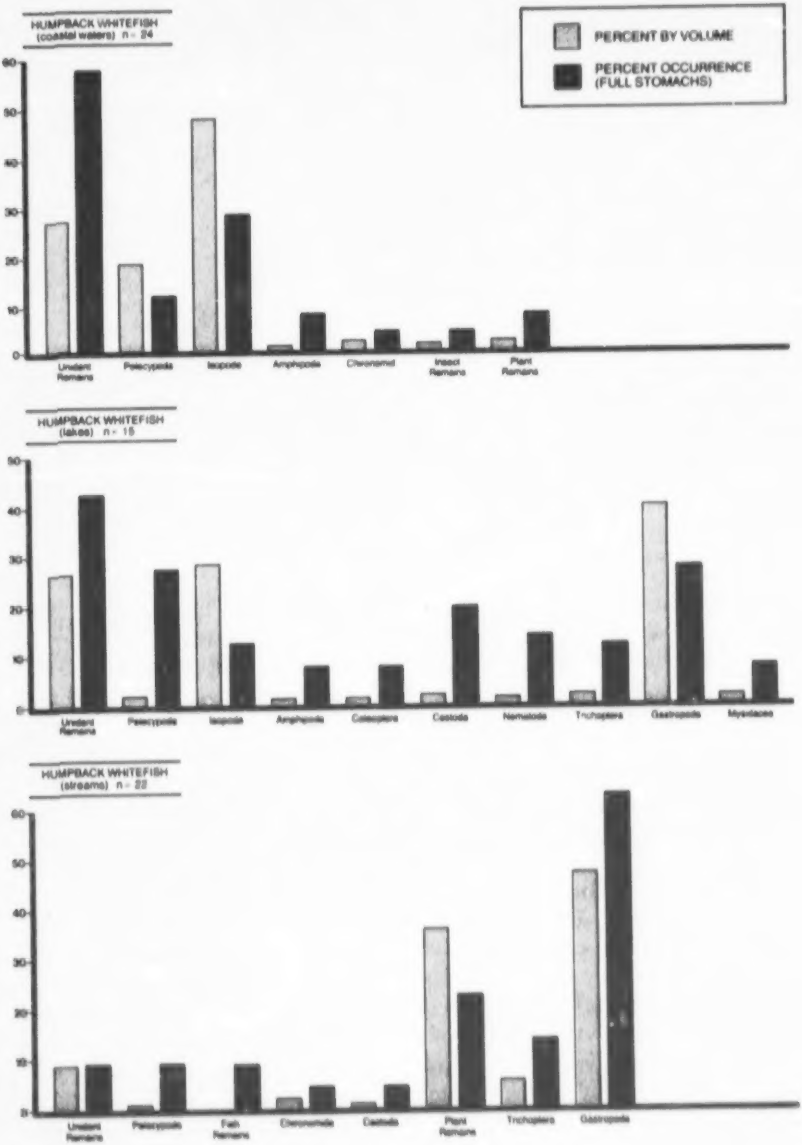


Figure 17: Stomach contents of humpback whitefish gillnetted in the outer Mackenzie Delta, from coastal waters, in lakes and from streams.

(mature char spawn every second or third year) are found moving upstream through the Delta in August and early September. Spawning takes place in late fall. Both spawning and non-spawning Arctic char overwinter in freshwater habitats, usually high in the watershed near springs.

The inconnu (French for "unknown"), were so named by Alexander Mackenzie's Canadian voyageurs. The "cony", as they are known today by Northerners, are important to native fishermen throughout the Mackenzie system. These large fish undertake long migrations, returning from the lower 1 000 km (600 mi) of the Mackenzie basin to feed and overwinter in the Delta and nearshore zone. Spawning grounds of the inconnu are in the upper reaches of the Peel, Arctic Red and Mackenzie rivers; the spawning period is September and early October. This is immediately followed by the annual downstream migration. Although amphipods, chironomids, mysids and isopods are routinely found in the stomach contents of inconnu, immature fish such as least cisco, ninespine stickleback, smelt, inconnu, sculpin and flounder are the more important prey.

Not only is the Mackenzie Delta an important migration corridor for anadromous fish, it is also a critical area for overwintering. Delta lakes with sufficient depth are known to be inhabited by whitefish and least cisco, as well as by a range of freshwater species. Arctic and least cisco, Arctic flounder, boreal smelt, inconnu and fourhorn sculpin have also been netted under the ice of Mallik Bay in winter. Smaller numbers of smelt, whitefish and least cisco have been taken through the ice of Kugmallit Bay. Many other areas suitable for overwintering are found along the northeast coast of Richards Island.

Only Arctic and least cisco, and fourhorn sculpin, have thus far been netted during the winter along the Yukon shoreline, all of these at Shingle Point near the western limit of the influence of the Mackenzie River. It should be noted that knowledge of fish overwintering locales within the entire southern Beaufort Sea area is distinctly lacking.

Fish harvesting

The harvesting of fish and wildlife is important to the Inuit residents of the southern Beaufort Sea region. The benefits are both commercial and nutritional. Although methods of hunting have changed dramatically since the coming of the whites, the Inuit continue harvesting animals along the coast and out on the nearshore sea ice. It is difficult to accurately estimate the degree of

ROGER PERCY

▲ Muktuk drying. Note flensing knives.

wildlife utilization, its economic value and relative importance to the users.

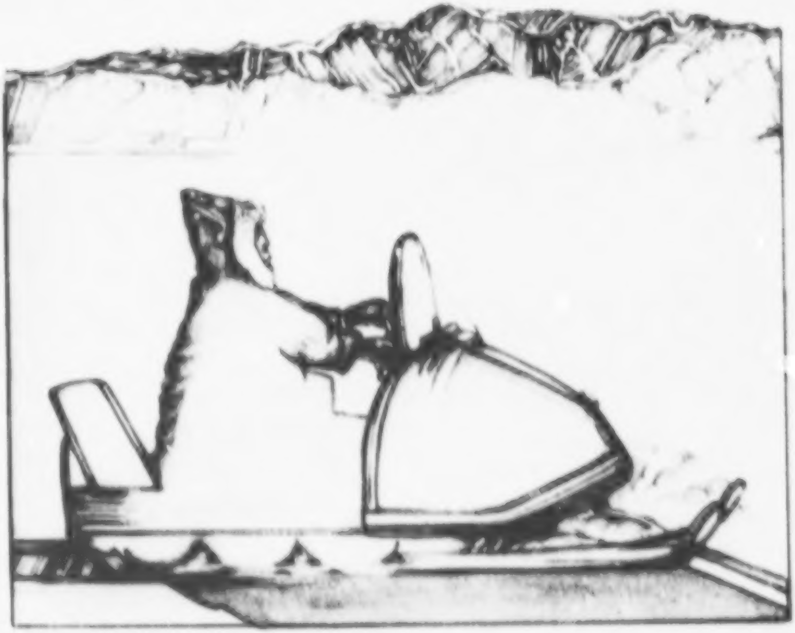
There are two "economies" in the region: the "Mackenzie economy" (which includes Aklavik, Inuvik and Tuktoyaktuk), and the "Rim economy" made up of three more isolated settlements: Holman (on Victoria Island in the Amundsen Gulf), Sachs Harbor (on Banks Island), and Paulatuk (on Cape Parry). With a combined population of roughly 400 individuals, these Rim communities are dependent on marine wildlife for food, cash and recreation; Arctic fox and seal, along with fishing, are particularly significant. Aklavik, Inuvik and Tuktoyaktuk have a much more diversified economic base. Salaried employment is prevalent even though it is often seasonal. The domestic fishery and annual whale hunts are, nevertheless, important to the residents of these settlements, in part due to the high cost of consumer goods brought in from southern Canada.

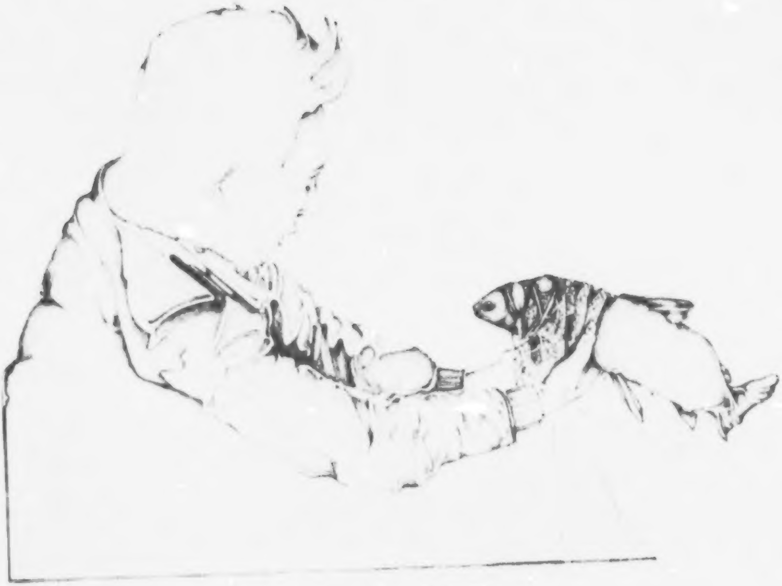
In the early 1970s, hunting, trapping and fishing employed one-fifth of the Indian and Inuit inhabitants of the Beaufort Sea region. Such activities are extremely important, even to those native peoples who are not economically bound to the fish and wildlife resources. Fishing requires a minimum of gear and effort; it provides smoked, frozen and dried food for people as well as food for dogs. Fishing is also a dependable source of fresh food throughout most of the year. The major species caught for human consumption are mostly freshwater or anadromous; they include Arctic char, lake trout, whitefish, pike, inconnu and herring. Burbot and suckers are often used for dog food.

When motorized skidoos came into common use for winter transportation, the importance of fisheries in the North decreased with the declining use of sled dogs. The snowmobile, and improved air travel, resulted in a migration of natives from isolated camps to the settlements. However, pet dogs remain the major consumers of fish. Other factors that have decreased the importance of fishing include the growth of wage employment.

Commercial fishing

Two types of commercial fishing take place in the Mackenzie (Aklavik, Inuvik and Tuktoyaktuk) economy. The export fishery is restricted to whitefish sold in the Prairie provinces. These fisheries are hampered by erratic catches, the perishability of the product, and the high cost of transportation. Quotas for this fishery are depressed by the pre-emptive status of domestic fishing plus a lack of information on domestic harvests and sustainable yields. The difficult logistics of Arctic commercial fishing and the abundance





Untangling whitefish.

of other fisheries with competitive advantages in southern markets, limit whitefish exports.

Opportunities to sell fish in the North are limited to retail foodstores, restaurants and direct sales to those native and white households with wage employment. The Yukon coast char fishery is typical of commercial fisheries in the Mackenzie economy. Menzies Fisheries, an Edmonton firm, operated in 1965 and 1966 between Inuvik, Herschel Island and Ptarmigan Bay on the mainland, south of the Island. The 1965 season was financially unsuccessful and the fish collection barge was lost in drift ice prior to 1966. To make things worse, the 1965 catch is believed to have exceeded the sustainable yield. Given the facts that catch limits were broken and the fishermen underpaid, the most significant thing about this fishery was its unprofitability. Since then no commercial fishery has taken place along the Yukon coast.

Another case is that of the Holmes Creek fishery. This began in 1963 when the Department of Indian Affairs and Northern Development set up a small operation 80 km (50 mi) north of Inuvik on the East Channel of the Mackenzie River. Three fishermen were paid $5,000 for their catch and the processing work done by their families. No fish were sold. The next year, the number of fishermen doubled while the catch remained the same. Family incomes dropped to $833 and again no fish were sold. Due to the economics, this fishery was abandoned in 1964 although native food fishing continued at the site.

The Holmes Creek commercial fishery was revived in 1972 by the Territorial government. In its first three years of operation, problems continued to arise and it remained a sub-marginal fishery, dependent on price subsidies and guaranteed payments to fishermen. The income from an annual quota of 50,000 fish totalled $12,000 in 1973 and was divided between three families. This income is subsidized; the fishery cannot be considered of socio-economic importance.

The remaining commercial fisheries in the Mackenzie economy are individual operations which sell whitefish, lake trout and Arctic char. Eight fishermen were licensed in 1974 and 1975. Four supplied fish to Inuvik, three to Aklavik, and one reported no sales. Catch records indicate that fishing incomes rarely exceed $1,000. Only 11 families are involved here in commercial fishing, averaging less than $2,000 in annual income from this source. Over half of the total income is earned from the subsidized fishery at Holmes Creek. Commercial fishing provides one percent of the earned income in the Mackenzie economy and involves less than six percent of the families.

In the Rim economy (Holman, Paulatuk and Sachs Harbour), there is only one fishery that provides cash income for the natives, the char fishery at Paulatuk. This fishery was established in 1968 with a 2 300 kg (5,000 lb) quota. The char was sold in Inuvik by the Paulatuk Co-op; the fishermen were paid 50¢ a pound for their catch. In the early years of this fishery (1968-73), char was a staple in the diets of both the people and dogs of Paulatuk. Because char was saleable, the community switched to eating whitefish and burbot. Income from char fishing went from $147 each for 17 fishermen in 1974 to $689 each for 11 fishermen the following year when the quota was doubled and the landed price increased to 85¢ a pound. Income from commercial fishing approximated one-third of the total earned income in Paulatuk during 1969.

Domestic fishing

Domestic fishing provides an excellent example of the differences between the Rim and Mackenzie economies. Fishing in the Rim communities of Paulatuk, Holman and Sachs Harbour is done as recreation. It provides both diversion and a welcome change in the diet. The average annual catch per family in Sachs Harbour, for instance, is only 55 fish. This is in marked contrast to

JIM BUNCH

▲ Fish drying at Tuktoyaktuk; DEW Line radar station in background.

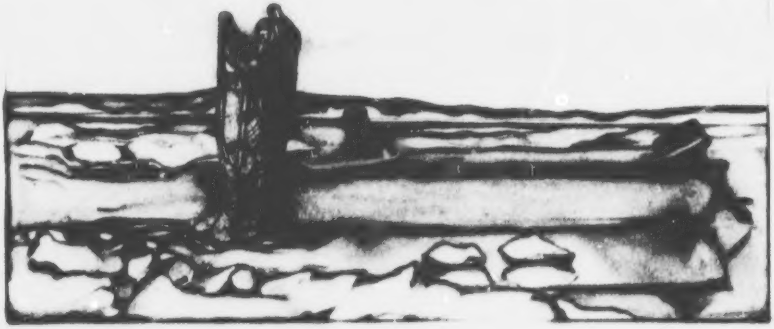
the Mackenzie economy where domestic fishing is a mainstay of wildlife utilization by the people.

A number of freshwater and anadromous fish species are harvested in the Mackenzie Delta region; the estimated total annual catch amounts to one-half million kg (1.2 million lbs). Studies made in Aklavik suggest that the bulk of this catch (77 percent), is used to feed the large dog population. At present there is virtually no exploitation of marine fish species although the potential certainly exists. Historically, Pacific herring and capelin have sustained important local domestic fisheries. (They are also essential prey for marine mammal and bird populations which in turn make a significant contribution to the economy of the region.)

The domestic fishery is most intensive during the open water period, especially during the spring and fall migrations of anadromous fishes. Fishing is also carried out along the coast by families temporarily situated at summer whaling camps. No extensive winter fishery has developed in the Beaufort Sea or Mackenzie Delta, although fish returning from their spawning runs are sometimes intercepted by through-the-ice net fishing. Setting gill nets beneath six feet of river or lake ice is a difficult undertaking. Large numbers of burbot (a freshwater member of the cod family), are jigged through the ice in February often using the traditional handmade bone hooks; the burbot liver is considered a delicacy by people of the inner Delta. Likewise, lake trout are caught in Eskimo Lakes by Tuktoyaktuk residents.

Domestic fishing extends from Herschel Island, about 130 km (80 mi) west of the Delta, to the eastward end of the Tuktoyaktuk Peninsula. The main activity, however, centers on the Delta and in the vicinity of Tuktoyaktuk (Figure 18). This fishing is not regulated by quota and catch records are not kept. Fish consumption is usually estimated by projecting the assumed "requirements" necessary to support the population of dogs and people. Table G is such a projection of native food catch in the Mackenzie economy.

The major difference between the Rim and Mackenzie economies is the number of people dependent upon marine wildlife. In the Mackenzie economy, only a few of the people are actively engaged in hunting, trapping and fishing, (although a larger segment of the population shares in the benefits from wildlife resources). In contrast, most of the people of the Rim economy depend upon marine wildlife for their livelihoods. The remote communities of Holman, Paulatuk and Sachs Harbour do not reap many of the benefits that accrue from offshore petroleum exploration such as



Coastal gillnetting.

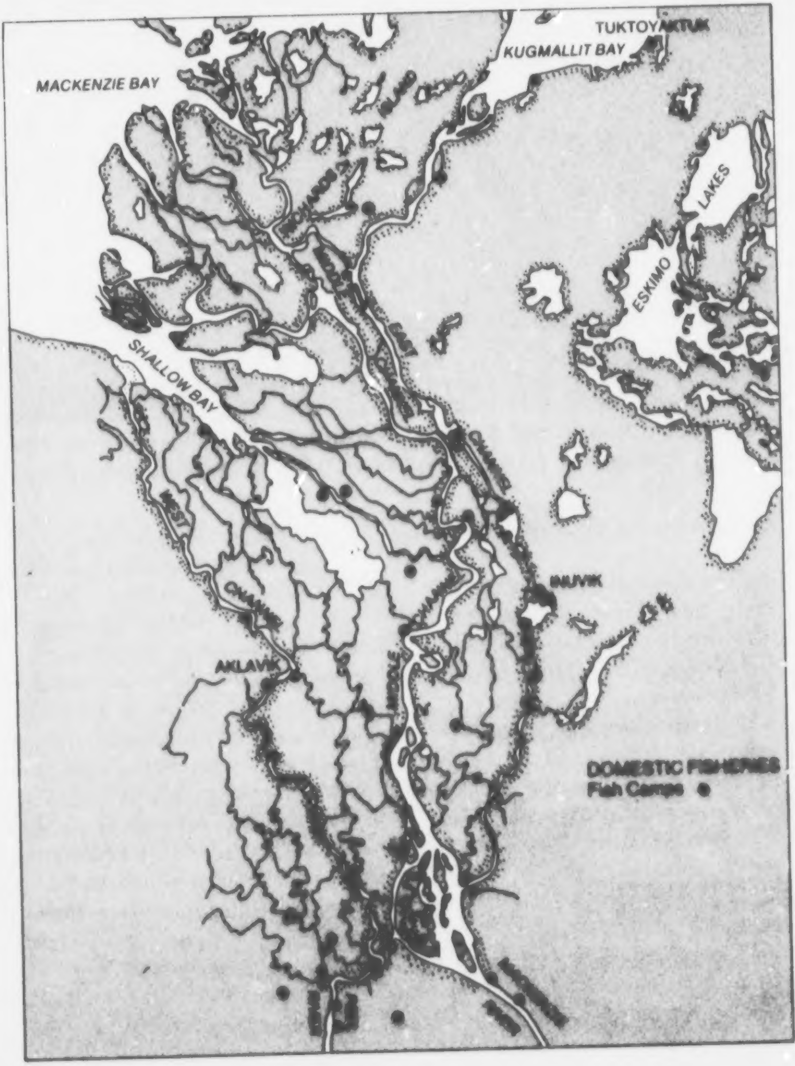

TUKTOYAKTUK
KUGMALLIT BAY
MACKENZIE BAY
LAKES
ESKIMO
EAST
SHALLOW BAY
CHANNEL
WEST
INUVIK
CHANNEL
AKLAVIK
MIDDLE
DOMESTIC FISHERIES
Fish Camps ●

Figure 18

Table G
Projected domestic fishing catch, value and use for Mackenzie area of Beaufort Sea (from Brakel 1977).

Community	Fishing population People*	Fishing population Dogs**	Total catch (lbs)	Human food[1] ($)	Dog food[4] ($)	Total value ($)	Per capita value ($)
Aklavik	677[1]	172[1]	294,476	20,400	67,943	88,343	130.49
Inuvik	300[2]	15[3]	99,740	24,000	5,922	29,922	37.40
Tuktoyaktuk	570[2]	85[3]	172,860	18,300	33,558	51,858	90.98
Mackenzie economy:	1,547	272	567,076	$62,700	$107,423	$170,123	$86.29 (avg)

* Inuit, Dene and Metis fishermen and their families.
** Dog population for fishing families - not community.
[1] Aklavik fish utilization study, Fisheries and Marine Service.
[2] DIAND, Mackenzie Manpower Survey 1969.
[3] Estimated.
[4] Valued on the basis of 30¢ per lb.

The Aklavik survey data in this Table indicates that 45 percent of the families consumed 97 percent of the fish. One-third of this group fed fish to 7 or more dogs, and consumed three-quarters of the fish. Although the average person ate 100 lbs of fish, and 90 percent of the families ate fish, any reduction in domestic fishing is more likely to result in hungry dogs than in hungry people.

ROGER PERCY

▲ Inuit whaling camp.

wage employment and better social services. They will, however, suffer the most if industrial development results in a gradual deterioration of marine wildlife and its habitat. Their traditional lifestyles could be irretrievably lost.

Arctic Ocean and Beaufort Sea

The polar ocean that lies between North America and Asia is almost completely covered with a mantle of ice that dates back to the late Pleistocene Era of 50,000 years ago. This ice layer averages between two and three metres (6-10 ft) in thickness during the winter, and only melts at the peripheries in the summer. In oceanographic terms, the boundaries of the Arctic Ocean could be considered to be a line drawn from the northern tip of Greenland through Lancaster Sound, past Baffin Island to the coastline of the northern Canadian land mass. The line would continue westward to Alaska, across the Bering Strait, back along the Siberian coast to Novaya Zemlya, over to Spitsbergen and return to Greenland (Figure 1).

The central polar basin, roughly triangular in shape, is rimmed by continental shelves which are breached only by the deep passage running through Fram Strait to the Greenland Sea. The continental shelf along the North American coast is only about 100 km (60 mi) wide, but on the Asian side it averages 640 km (400 mi). The Arctic Ocean consists of two major basins, the Canada Basin and the Eurasian Basin, separated by a range of undersea mountains known as the Lomonosov Ridge (having a sill depth of 1 400 m/4,500 ft). The Canada Basin (greatest depth 4 000m/ 13,000 ft), is the larger of the two but the Eurasian Basin is the deeper, (5 100 m/16,500 ft).

The most important channel connecting the Arctic and Atlantic oceans is the Fram Strait (Figure 24). Over 75 percent of the total exchange of water between the two oceans flows through this passage between Greenland and Spitsbergen. The flow from the Pacific to the Arctic oceans is via the Bering Strait and amounts to about 15-20 percent of the total input. The remaining one or two percent of water coming into the Arctic Ocean originates as precipitation and river outflow. With the exception of the Mackenzie, all the major rivers enter the Arctic Ocean on the Siberian side. The total freshwater addition to the Arctic Ocean is an estimated 100 000 m^3/sec.

To maintain sea level as a global constant, the inflow and outflow of water in the Arctic Ocean must balance. While most of the water exchanged does so through the Fram Strait, the Pacific Ocean and freshwater inputs are offset by an outflow south and east through the Arctic Archipelago. Part of the freshwater outflow from the Arctic Ocean exits through Fram Strait in the form of low-salinity ice carried by the East Greenland Current. Oceanographers are able to monitor these movements by careful measurements of water mass properties such as temperature, salinity, density and chemical characteristics.

Hydrography

The mapping of the islands and coastline of the Canadian Arctic was begun by the early explorers in their wooden ships. Understandably, due to the impassable ice fields, their maps and charts were rudimentary. Where it was possible to do so, they made soundings of the ocean depths. Prior to 1875, these measurements were made with a lead weight attached to a hemp line. For the next half-century, piano wire was used instead of hemp, and soundings were taken through the sea ice and from the ice edges, as well as from ships. In the 1950s modern technology in the form of high-resolution echo sounders and precise positioning systems, often using helicopters, permitted the Canadian Hydrographic Service to publish more accurate charts of some principal navigation routes in the Arctic.

A need for further charting of Arctic Ocean bottom topography came with the construction in the mid-1950s of the DEW Line radar stations across Canada's northern coastline. The need was to delineate all the navigable channels leading to and from the radar sites to permit the safe passage of freight-carrying ships. A great deal of the charting during these years was carried out by hydrographic vessels of the United States Navy. Continued impetus to the task was provided by the oil industry during the 1960s and 1970s. Mineral exploration was and is going on in various parts of the Arctic; this has meant even more ship traffic and the need for verification and correction of existing hydrographic data as well as the inclusion of greater detail. One such area is the Beaufort Sea.

The Beaufort, offshore from Tuktoyaktuk Peninsula to a distance of about 140 km (86 mi), is underlain by the Continental Shelf. Until 1969 the Shelf was thought to be all plateau. In that year, the icebreaker CCGS *Sir John A. MacDonald* discovered the first known underwater pingo. (A pingo on land is volcano-shaped; a huge mound formed when a lake bottom froze down to the permafrost and heaved up in a gigantic boil during the last Ice Age.) Submerged pingo-like features as high as 45 m (150 ft) have

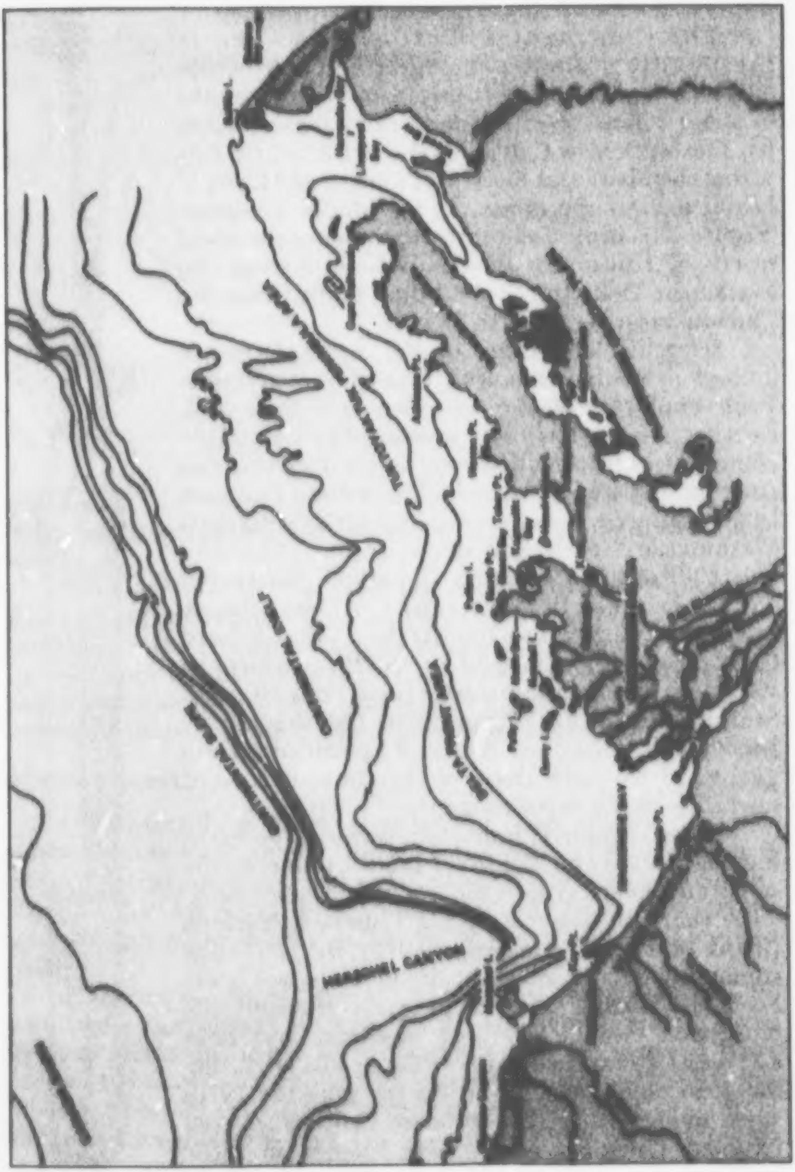

HERSCHEL CANYON

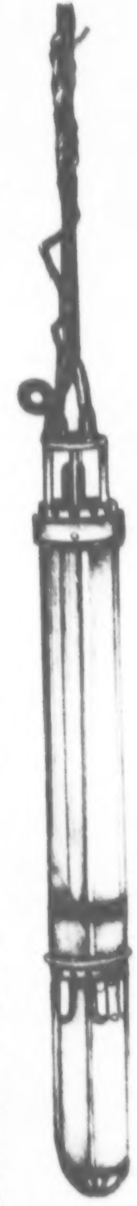
Figure 19

since been charted within 12 m (40 ft) of the sea surface. The locations of over 1,000 such underwater features have now been mapped.

The Continental Shelf declines gently northwards to the outer edge (the Continental Slope), where it drops abruptly from average depths of about 200 m (660 ft) to depths of 1 000 m (3,300 ft). The Mackenzie Canyon, a V-shaped trench, cuts across the Shelf and Slope from north of Herschel Island to near the mouth of the Mackenzie River (Figure 19), while a minor trough incises the Shelf north of Kugmallit Bay. Northward from the Mackenzie Delta the sea bed dips sharply into the Canada Basin of the Arctic Ocean.

Scientific knowledge of the Arctic Ocean is limited in comparison with that of warmer seas. Polar explorers of the late 19th and early 20th centuries were basically looking for navigable routes. Some information was gathered about ocean currents and sea ice but biological phenomena were largely ignored. Later explorers such as Adolphus Washington Greely (Ellesmere Island, 1881-84), and Vilhjalmur Stefansson (Beaufort Sea region 1913-18), were in the Arctic for the primary purpose of gathering scientific data. (The ill-fated Greely Expedition lost 19 of its 25 members to starvation and accident before rescue was effected. Stefansson, an anthropologist, led the highly successful Canadian Arctic Expedition. Data gathered by both these government-funded operations is still in use today.)

Stefansson made soundings through the ice of the Beaufort Sea but the first scientific report on the subject of oceanography did not appear until 1952. That year, the Journal of the Fisheries Research Board of Canada carried a paper by J.P. Tully containing data collected by the RCMP patrol vessel *St. Roche* during its two journeys through the Northwest Passage (1940-42 west-east; and 1944 east-west). Occasional papers were produced during the 1950s and 1960s but it was not until the 1970s when interest in arctic petroleum deposits sparked renewed Canadian government interest in arctic geography. During this same time, Russian and



Electronic probe for measuring salinity and temperature.

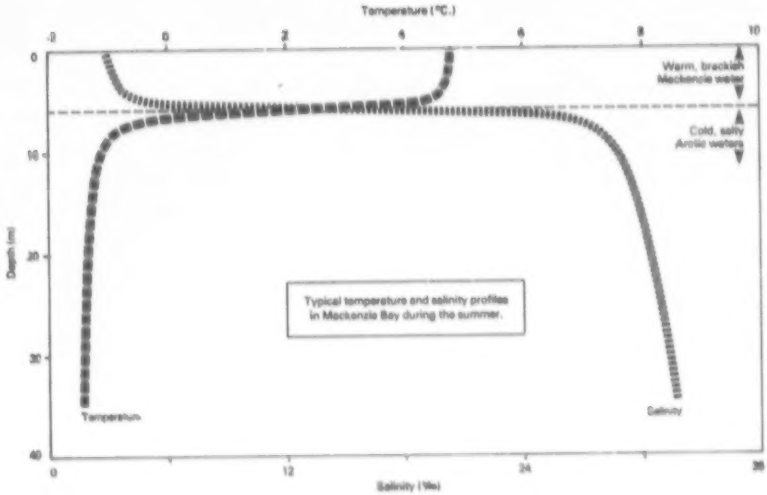


Figure 20

American scientific teams have added to our knowledge of arctic waters.

An integral part of the Arctic Ocean is its ice cover. Although it is not a complete cap at any time of the year (parts of it being in motion with leads opening and closing), the blanket of ice reduces the exchange of heat and water vapor that takes place between the ocean and atmosphere. The heat budget of the Arctic Ocean is still not well understood but "cold water" research is ongoing.

Water masses

Oceanographers know that density and salinity of water masses inhibit their mixing. Layers form and, in the absence of a mixing energy (such as storm-induced waves), remain quite stable. These water layers can move in different directions, at different speeds, with some mixing occurring at the boundaries between masses.

Water masses, even those at great depths, can be identified by measuring parameters such as salinity and temperature. These measurements are made by instruments that are lowered from surface to bottom, or by collecting samples at specified depths and analysing the water column. Sampling is generally done from a stable surface platform such as a ship or ice sheet. Measurements obtained using either method can then be plotted on a graph similar to Figure 20 to produce an STD (salinity, temperature and depth) profile. As well as providing clues relative to the depth of sub-sea water masses, an STD profile can delineate fine-scale stratification.

Arctic surface waters are characterized as being relatively dilute (i.e., low salinity due to river run-off and ice melt), of low density and cold (temperatures around freezing). This layer extends from surface to about 250 m (800 ft) and is subject to variations in temperature and salinity. The variability is the result of seasonal changes such as freeze-up and thaw and proximity to source water such as rivers or inflowing ocean water masses. Since the transition from the Continental Shelf to Continental Slope occurs between 200 m and 300 m (660-1,000 ft), nearshore waters are almost entirely of this type.

Ice formation and ice melt, plus freshwater river discharge, are the principal influences on salinity of the surface waters. During freezing, salt is lost to the water below, increasing its salt content. Conversely, sea ice that is melting dilutes the salinity of the

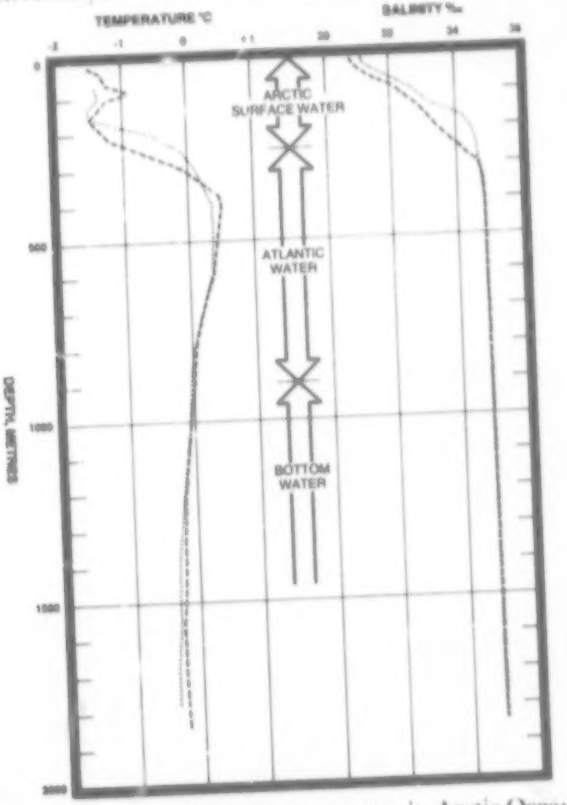


Figure 21: Layering of water masses in Arctic Ocean.

surrounding water. Although the Mackenzie River has by far the largest effect on the south Beaufort Sea, it also exhibits the greatest seasonality of effect.

The upper 250 m (800 ft) of the Arctic Ocean (Figure 21) comprise its surface water, a water mass characterized by a pronounced density stratification. This results from the sharp increase in salinity downward through the water column. This density stratification is important since it prevents any deepwater convection from developing within the Arctic Ocean. It also prevents the heat from the underlying "warm" Atlantic water from reaching the surface. The relatively low salinity at the surface is maintained against the upward diffusion of salt by the addition of fresh water, principally through river outflow.

The topmost 30-50 m (100-165 ft) of surface water tends to be

Average surface temperatures for the open water season (1954 – 1970) in the southern Beaufort Sea.

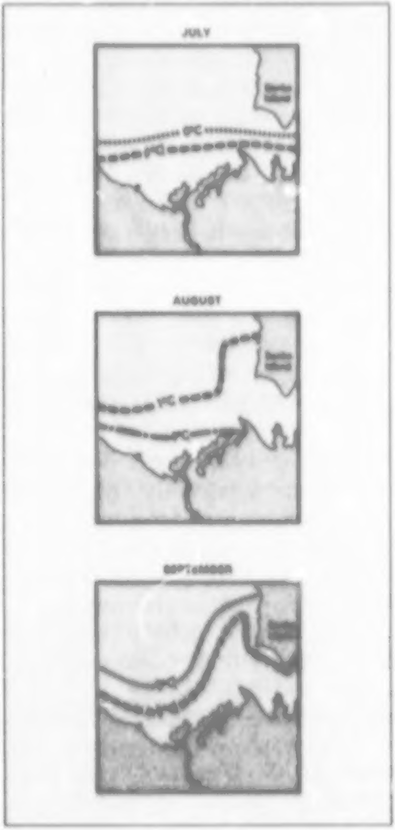


Figure 22

uniform vertically in both temperature and salinity. Except for areas such as the southern Beaufort Sea which become ice-free in summer, the water will be near the freezing point. Away from the Mackenzie Delta, the salinity of the surface water ranges from 27-34^{o}/oo, with a gradual increase moving eastward from the Bering Strait to Fram Strait. In summer the salinity is slightly lower than in winter.

Below the 30-50 m depth there are two different subsurface layers. In the Eurasian Basin the salinity increases rapidly with depth to 34.9-35.0^{o}/oo at 200 m (660 ft), while the temperature remains below -1.5°C to 100 m (330 ft) then begins increasing, reaching 0°C at about 200 meters. This cold, saline water appears to be formed in the submarine canyons and near the outer edge of the Continental Shelf bordering the Eurasian Basin. In the Canada Basin the salinity increases less rapidly with depth, and there is a small relative maximum in the temperature between 50-100 m (but always less than 0°C), followed by a minimum of about -1.5°C at 150 m, before increasing to 0°C at 200-300 m. The subsurface high temperature maximum is maintained by relatively warm water inflowing from the Bering Sea in summer and mixing with the Shelf water, and the low temperature minimum is formed by water coming in from the Bering Sea in winter.

Below the Arctic surface water layer is the intermediate Atlantic water mass which lies between 300 and 500 m (1,000 and 1,650 ft). Water temperature below 300 m in this layer climbs to 0.5°C which is the maximum for the Arctic Ocean. It remains at this temperature throughout the intermediate level Atlantic water mass. Salinity remains at between 34.8^{o}/oo and 35.0^{o}/oo. Since, at low temperatures, the density of sea water depends almost entirely on salt content, there is virtually no density stratification beneath the surface layer.

Beneath the Atlantic water mass lies cold, nearly uniform bottom water. This lowest level water mass represents about 60 percent of the total water volume of the Arctic Ocean; if we add the Atlantic water layer, the total increases to 90 percent. The bottom water originates in the Greenland Sea, is mixed, and flows north through Fram Strait. It forms the densest water flowing into the polar ocean. Once there, it is nearly isothermal (temperatures characteristically being below 0°C). Salinities are high and of a very narrow range (34.90 to 34.99^{o}/oo).

Within each of the two major basins, but beneath 1 400-1 500 m (4,500-5,000 ft), a sharp temperature difference of nearly 0.5°C occurs across the Lomonosov Ridge. The 1 400-1 500 m level probably represents the effective sill depth for the ridge, below which a free exchange of water is prevented.

Circulation

The pattern of water movement in the south Beaufort Sea is complex, the result of many factors, on different time scales and at different depths. The flow of incoming waters to the Beaufort vary in their localization of effect but, over-all, do contribute to patterns of circulation. Major inflows are: Pacific salt water through Bering Strait and fresh water from the Mackenzie River. Other fresh water sources, more limited in their effect, include the Anderson, Blow, Babbage and Firth rivers. River inflow is aided by gravity, snowmelt and winds. The area of Beaufort Sea influenced is largely dependent upon the amount of runoff, the strength and direction of the winds, and the presence or absence of ice cover. The merging of fresh and salt water in the Mackenzie estuary results in wedge formations, previously discussed, with fresh water flowing out over salt water. Density gradients are set up, with mixing occurring at the interfaces between salt and fresh water. Mixing is aided by wind-induced waves at the surface and internal waves (which form between two water layers of different densities). The result is similar to ocean swells but at lower depths: slow, churning undulations.

Inshore, the general current moves parallel to the coastline, follows bottom contours and has a speed of about five cm/sec (2 in/sec) below the surface. Increased Mackenzie River flow in summer pushes the fresh water farther out to sea in a northeasterly direction at a speed of about 50 cm/sec (Figure 23). Offshore, the largest circulation feature is the Beaufort Gyre, extending from the edge of the Continental Shelf to the North Pole and to a depth of about 200 m (660 ft). The mean currents form a large, clockwise-rotating gyre which turns at the very slow speed of about two cm/sec, increasing to five to ten cm/sec north of Alaska (Figure 24). Over-all, the direction of movement in the upper waters has its ultimate cause in the prevailing wind pattern over the Arctic Ocean.

Much of our knowledge of the movements of Arctic surface water comes from scientific studies conducted on drifting ice islands, ice floes and ships. Since about 1974 researchers have been able to employ more advanced technology in the forms of current meters, radar and radio tracking of drifting drogues, and satellite imagery. We now know that currents in the upper waters tend to be relatively slow (ten cm/sec or less), and they correspond in both speed and direction to the motion of the sea ice. The Transpolar Drift Stream (Figure 24), is directed from north of the Laptev and East Siberian seas across the length of the Eurasian Basin, exiting through western Fram Strait as the ice-laden East Greenland Drift.

At its outset, the Transpolar Stream is slow (2-3 cm/sec), but past the Pole it picks up speed, increasing to eight to ten cm/sec as it enters Fram Strait.

As is the case elsewhere in the world, currents in the Arctic Ocean can vary greatly from what is thought to be their norm. An example of this occurs in the Canada Basin where oceanographers

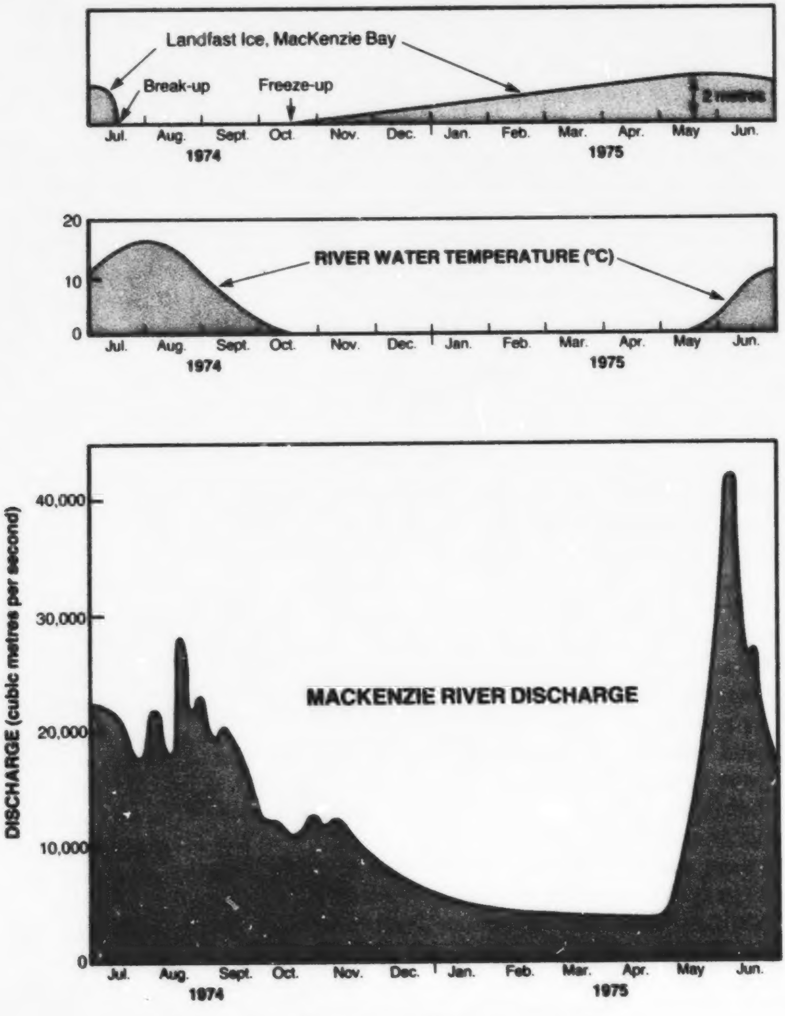


Figure 23: Mackenzie River seasonal flow.

have detected, on occasion, a circular, high-speed current (speeds higher than 50 cm/sec have been recorded), centered near the 150 m (500 ft) depth level and completely below the surface. These fast currents represent vortices, or eddies, ab[illegible] ten km (6 mi) across, which are being carried slowly around [illegible]n the ocean. Those observed so far are believed to originate in the Chukchi Sea. Other variable current conditions are associated with storms or changes in the prevailing winds, as well as with tides.

Our knowledge of the circulation of the mid-range Atlantic water mass (300-500 m/1,000-1,650 ft) has been inferred from temperature and salinity data. This water originates in the North Atlantic and flows northward in the Norwegian and West Spitsbergen currents, passing through Fram Strait. At this point the water is warm (+3°C) and highly saline (35⁰/oo). As it enters the Arctic Ocean it sinks due to its high salinity and moves easterly along the Eurasian continental slope, becoming colder and more dilute as it goes. The general circulation of the Atlantic water is counterclockwise and at very slow speeds (in the order of 5 cm/sec).

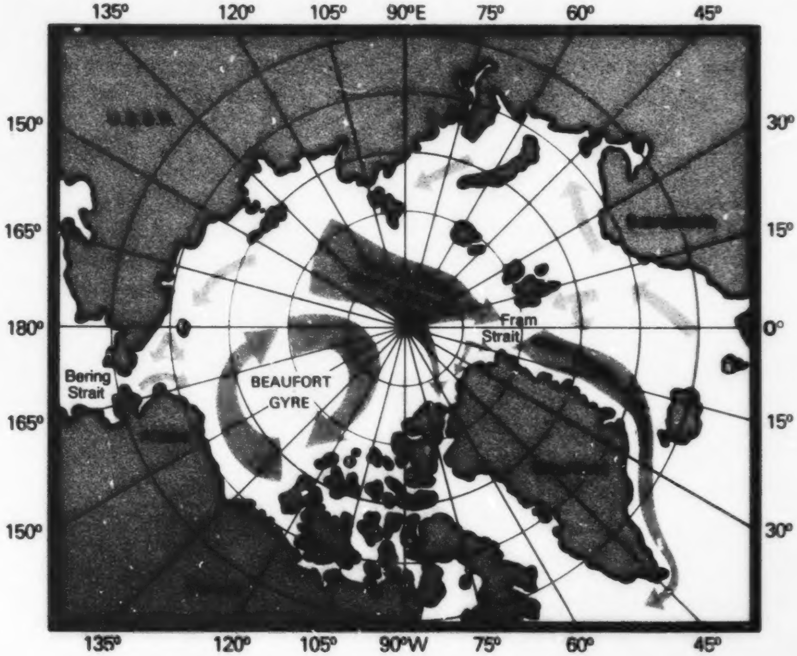
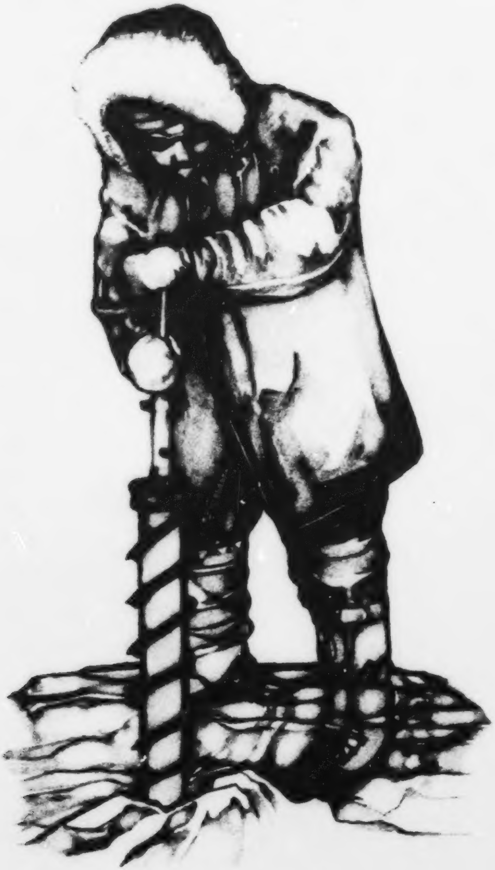


Figure 24: Circulation of Arctic surface water and ice.

The circulation of Arctic bottom water is less clearly understood. It is formed in the Greenland Sea, moves into the Eurasian Basin, crosses the Lomonosov Ridge and enters the Canadian Basin. The rate of movement and residence time of the waters in the Arctic Ocean are not known.

The greatest variability is to be found in surface-water currents, due primarily to the effect of wind on open water. The influence of the wind has two components, horizontal and vertical. Water transport in any direction is dependent upon wind direction, speed and fetch (the distance the wind can blow across the water and thus build big waves). Coastal topography and ice



Ice core sampling.

conditions (more accurately, the amount of ice-free water), define the fetch of the wind. The size of the waves will be determined not only by the wind but by density gradients in the water as well.

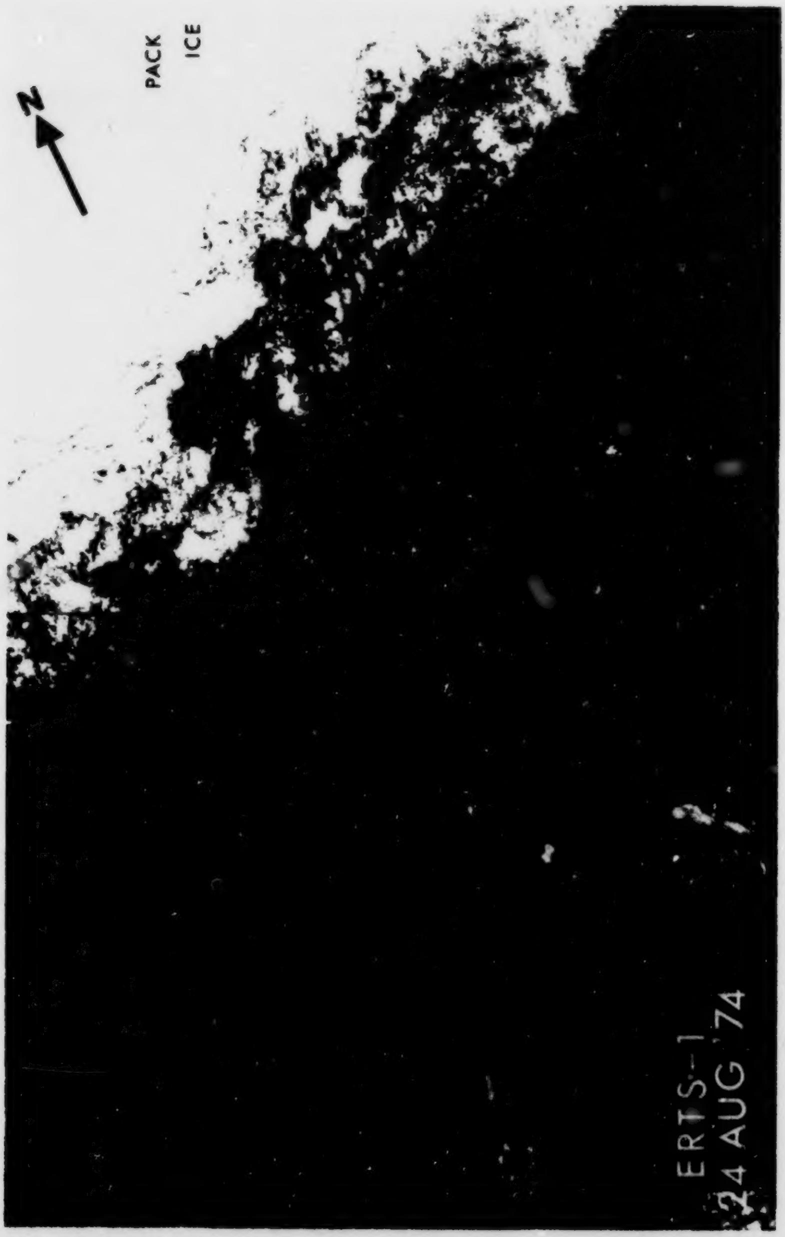
Wind blowing across the sea surface exerts a drag and imparts motion to the water. Initially, only the top few centimetres of water will be affected. But if the wind gets stronger, or blows continuously, the drag is transmitted downward in the water column, causing mixing to a greater depth and generating waves. A wind-driven current moves at a rate of about three percent of the wind speed; its direction of flow will be about 20 degrees to the right of where the wind is coming from.

In the southern Beaufort Sea, especially during the summer of a "good ice-year" (when there is lots of open water), the prime influence on the surface current is the wind. When the prevailing wind is onshore from the west or northwest, it sometimes results in surface water converging on the coastline of Tuktoyaktuk Peninsula at speeds of 60 m/sec (200 ft/sec). If the wind reverses its direction, the eastward flowing current will slow down and, if the wind continues from the east, the flow will change to westerly. The result will be a divergent flow (upwelling) of higher salinity water along the coast, as the fresh Mackenzie River water is pushed offshore. During calming or changing winds, the flow pattern of surface currents becomes confused as large eddies form. Two to three days may be required for a current to decay.

Sea ice

Sea ice, which is ice formed by the freezing of sea water, is an obvious feature of the Beaufort Sea. It comprises about 99 percent of all the ice found there, the other one percent being freshwater ice. The latter originates as either river ice or land ice. River ice is that which forms in the river mouth or is washed down as ice pans during the spring freshet. Land ice consists of ice islands which have calved from the Ward Hunt Ice Shelf north of Ellesmere Island. Ice islands can range in size from small to huge. Enormous islands 60 m (200 ft) thick and 700 km^2 (270 sq mi) have been recorded. These islands float, drifting with the currents of the Arctic Ocean, sometimes grounding in shallow waters, and all eventually decay and shatter.

Sea ice is by far the most important. In the Beaufort, it is divided into three regions (Figure 7). Landfast ice freezes and breaks up annually. It forms a continuous sheet of fairly smooth ice, anchored to the shore and/or bottom, and extends offshore to Continental Shelf depths of 30 m (100 ft). Figure 25 illustrates the annual growth and melting of the ice in the Beaufort region.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PACK ICE
ERTS-1
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▲ Satellite photo shows ice in drilling area.

▲ New ice forming, Tuktoyaktuk, October 1980. MARJ TRIM

Maximum ice thickness approaches two metres (7 ft) just before break-up in April or May.

Farther out to sea is the permanent ice field of the Arctic Ocean: the polar pack. It is an accumulation of recently formed ice, of old ice which has survived one or more summers, and even chunks of ice that formed against a coastline and contain embedded gravel. Outside of sheltered bays, sea ice is in continual motion due to winds and currents which are in turn influenced by the atmospheric high pressure system centered over the Canada Basin during much of the year. This clockwise motion of the polar pack is due to the Beaufort Gyre (Figure 24).

Weaker parts of this moving canopy fracture when stresses become too great, either due to the forces of compression or of shear. They pull apart, exposing an openwater "lead" or, conversely, pile block on block to form a pressure ridge. These ridges may develop in ice of any thickness, from thin sheets only ten cm (4 in) thick to huge blocks three metres (10 ft) in thickness. The ridges may cantilever upwards into "sails" 14 m (45 ft) high while below the surface extends a 50 m (160 ft) keel. Despite this, relatively flat expanses of polar pack do occur.

Included in the pack are ice floes and islands of all sizes, shapes and ages. Large floes range upwards to 2 000 m (6,600 ft) in their longest dimension. Breaking up the jumble are leads and polynyas. (A lead is a long fissure in the ice, often wide enough to be navigable

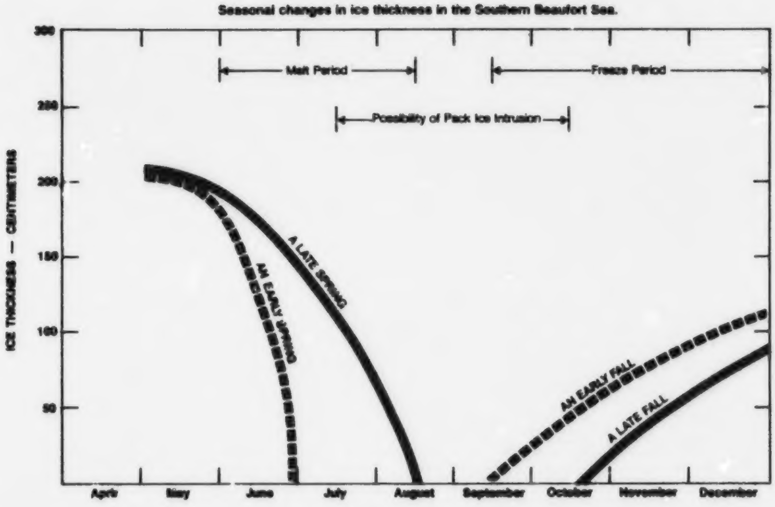


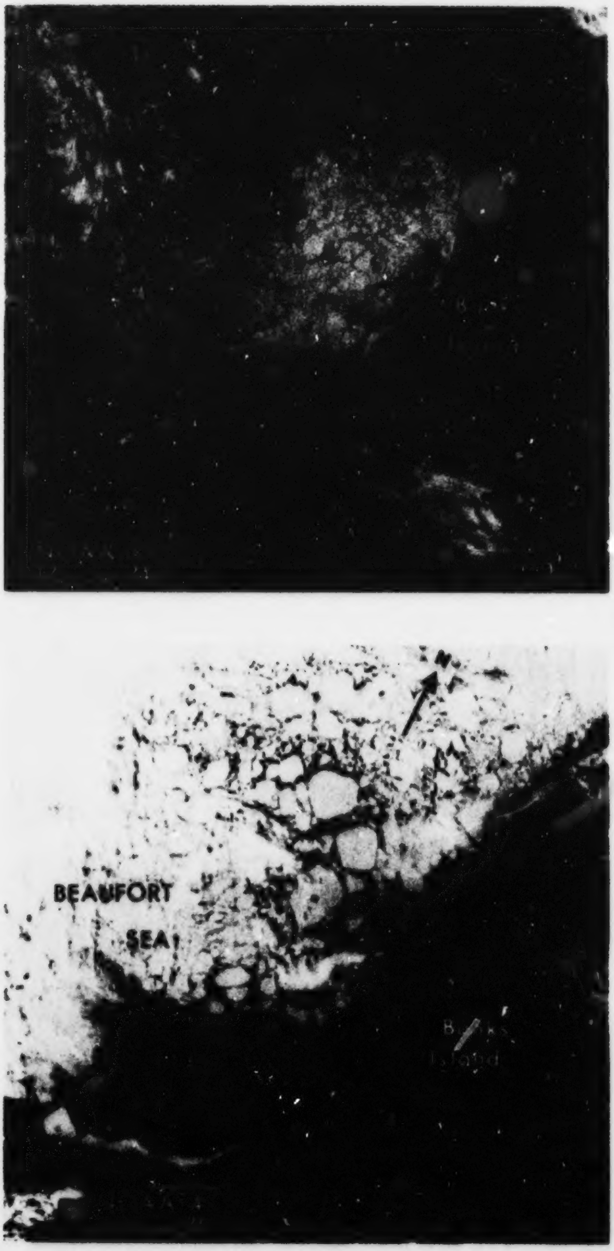
Figure 25

by ships; a polynya is an expanse of open water surrounded by ice.) The proportion of open water in the polar pack varies as currents and winds propel the floes closer together or farther apart. As the floes pass each other, they jostle and grind, causing shears and forming pressure ridges.

Between the landfast ice and the polar pack lies the transition zone. This is an irregular cover composed of both new and multiyear ice. Here the greatest amount of shearing and grinding occurs as the landfast ice grows seaward and the polar pack, powered by the wind, shoves shoreward.

Ice floes, like icebergs, have a draft three to four times their height. Just as pressure ridges are formed above water by rafting and grinding, pressure keels are formed below. During onshore or alongshore ice movements, these keels often gouge the bottom. Much of the sea floor of the Continental Shelf undergoes extensive scoring by ice. It is common in depths of 15 to 45 m (50-150 ft), with maximum activity occurring around 30 m (100 ft) depth, in the transition zone.

At any time of the year, offshore winds (predominantly south and southeast) will move the polar pack northward, away from the coast and generally clearing the transition zone. Onshore winds have the opposite effect, forcing the polar pack closer to the shore. This latter situation developed and held for most of the summer in 1974, resulting in a very "poor ice-year" (a year when ice is constantly present in the near-shore and always in motion). In such


BEAUFORT
SEA
Banks
Island

Satellite images of Beaufort Sea's ice cover.

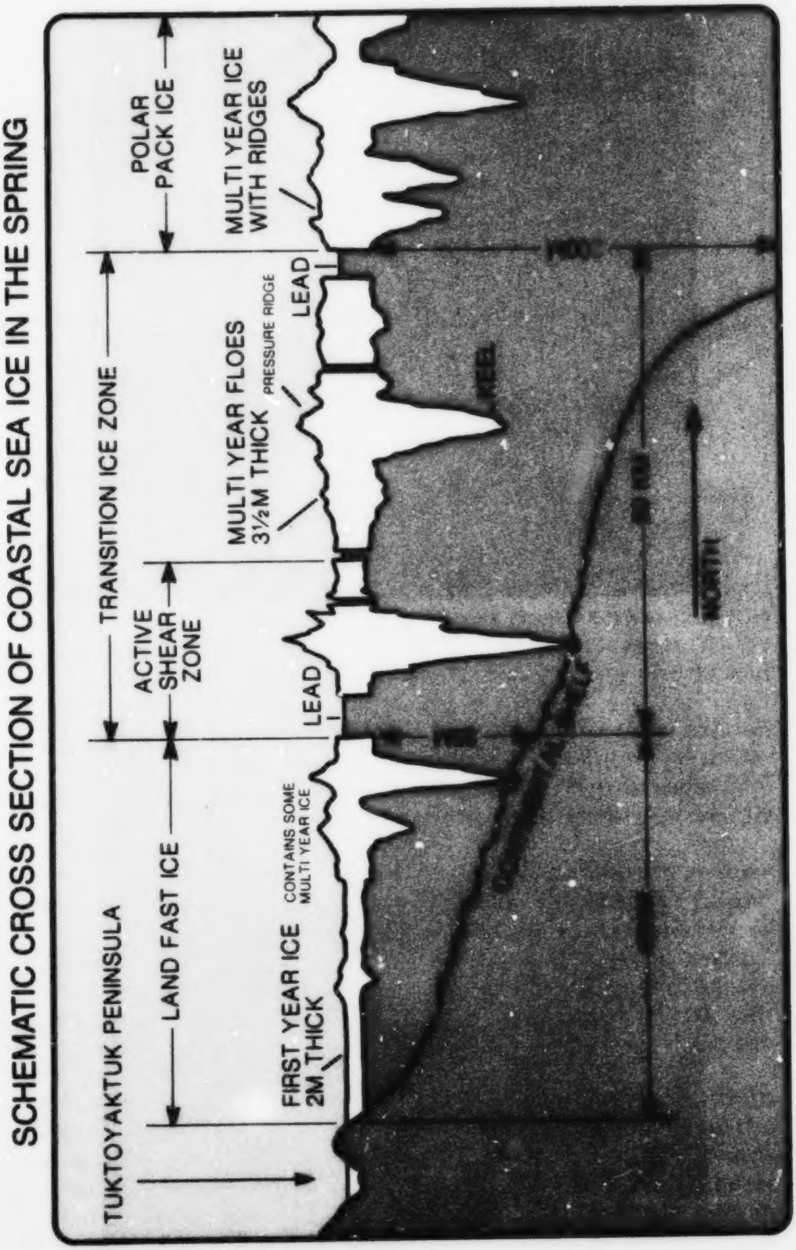

SCHEMATIC CROSS SECTION OF COASTAL SEA ICE IN THE SPRING
TUKTOYAKTUK PENINSULA
LAND FAST ICE
TRANSITION ICE ZONE
ACTIVE SHEAR ZONE
POLAR PACK ICE
FIRST YEAR ICE 2M THICK
CONTAINS SOME MULTI YEAR ICE
LEAD
MULTI YEAR FLOES 3½M THICK
PRESSURE RIDGE
LEAD
MULTI YEAR ICE WITH RIDGES
KEEL
NORTH

Figure 26

conditions the use of surface vessels for fisheries research, for example, is restricted to those with reinforced hulls which are able to withstand the pressure of ice closing in around them. Also, the decaying floes will not support the weight of landing aircraft employed in oceanographic studies.

Ice seasons in the Arctic can vary by about one month, from year to year. The formation of landfast ice has generally begun by late September. Its growth, both seaward and downward, continues all winter until the following May when landfast ice attains a maximum thickness of two meters (7 ft) and fringes the entire Beaufort Sea mainland coast (Figure 26). During its seaward advance it may incorporate some multi-year ice. This occurs when onshore autumn winds blow drifting ice into the newly-forming landfast ice. The outer (northern) edge of the landfast ice may become anchored by pressure ridge keels of the multi-year ice.

The nearshore boundary of the polar pack in winter generally lies over the seaward edge of the Continental Shelf. Stresses in the pack ice cause fractures and leads to open up but these quickly refreeze, forming patches of first-year ice in among the floes. In the dead of winter the ice sheet is quite stable in the Beaufort Sea.

The arrival of spring in the Beaufort varies but generally begins in March with an increase in south and southeast winds. Leads open, particularly west of Banks Island and at the mouth of Amundsen Gulf. Gradually these inter-connecting waterways spread to form a large polynya. The melting of sea ice begins in June. By this time the Mackenzie River is in flood and this hastens the clearing of the ice out of Mackenzie and Kugmallit bays. The general progression of break-up is from south to north and west to east. By early July, coastal landfast ice is free and drifting. In a "good ice-year", prevailing winds will hold the polar pack offshore. However, if west and northwest winds persist the polar pack will remain against the outer edge of the landfast zone. If this condition holds throughout the summer, it will be a "poor ice-year" (Figure 27). Predicting ice conditions is difficult because polar pack ice may persist in the nearshore area during any month of the openwater season.

Plant growth

Certain qualities determine the biological productivity of an ecosystem. In the Beaufort Sea, as elsewhere, the production of the free-floating microalgae known as phytoplankton depends on sufficient light and nourishment. Phytoplankton are much more abundant in nutrient-rich coastal waters than they are in the

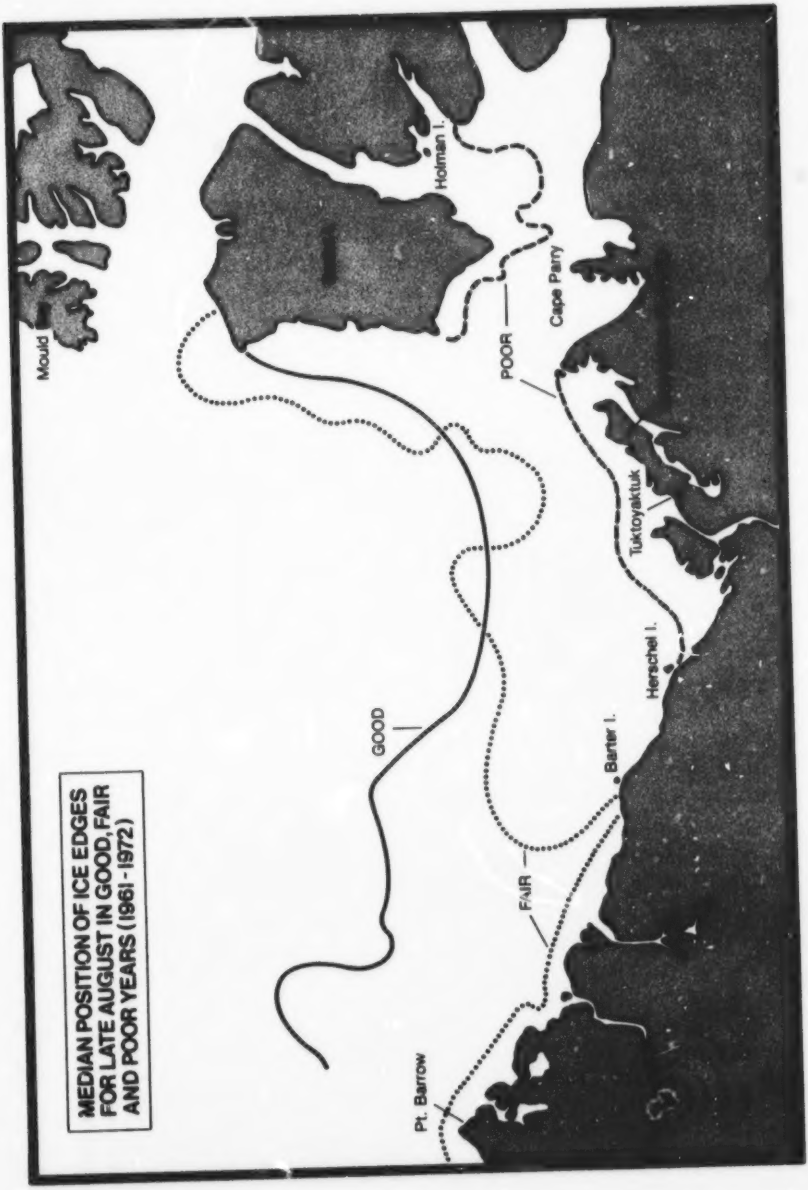

MEDIAN POSITION OF ICE EDGES FOR LATE AUGUST IN GOOD, FAIR AND POOR YEARS (1961 - 1972)
Mould
Holman I.
Cape Parry
POOR
Tuktoyaktuk
Herschel I.
Barter I.
GOOD
FAIR
Pt. Barrow

Figure 27

offshore ocean. They are the primary producers upon which large and small marine animals feed, the basis of most aquatic food webs.

Plankton organisms are small, mostly microscopic, and have little or no power of locomotion. They are distributed by water movements. There are two main types: phytoplankton and zooplankton. The former includes all of the floating plants such as diatoms and dinoflagellates. Zooplankton are the floating or weakly swimming animals which feed or "graze" on the phytoplankton. The major determinant of phytoplankton productivity is the radiant energy of the sun. Amazingly, less than 0.3 percent of the incident solar energy in the water column is converted by the diatoms and dinoflagellates to provide the basic food of the world's oceans.

The presence of ice cover for most of the year restricts, but does not prevent, primary production in the Beaufort Sea. Sufficient light can penetrate ice to support rudimentary algal growth along the edges and undersides of floes and sheets. As the season advances, open water enhances light conditions (and thus plant growth), while turbid waters, such as those of the Mackenzie River plume, inhibit light. Nevertheless, the plume area of the estuary is rich in nutrients washed down by the river and recycled from the ocean floor by upwelling. The result is an abundance of plant and animal life in the southern Beaufort Sea during the long daylight hours of summer.

The physical characteristics of the Beaufort Sea also contribute to its biological productivity. For instance, the first leads begin to open west of Banks Island and at the mouth of Amundsen Gulf. These leads are the first continuously open water of the year exposed to sunlight. Enhanced productivity is characteristic of such areas. Phytoplankton blooms, invertebrates and fish are abundant and even seals and whales utilize the leads for feeding and travel. Just prior to freeze-up (in late-September or early-October), autumn winds and a diminished Mackenzie River inflow result in a thorough mixing of the southern Beaufort Sea. Thus it is that when the leads first open in the spring, nutrients are available to foster plant growth. Phytoplankton depend on the availability of nutrients and carbon dioxide in the water around them. Once these are depleted below a critical level, production ceases until the area is either replenished or the phytoplankton are transported to a more fertile region. In the Arctic, horizontal expansion of a bloom is hastened by the opening of leads.

Throughout spring and summer, waters along ice edges show increased biological activity. This may be due to offshore winds which keep the polar pack out to sea and, at the same time, cause upwelling of nutrients at the ice edge. Studies indicate that the

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▲ Conducting primary productivity study in melt pond on sea ice. Balaena Bay, June 1975.

BILL ADAMS

numerous broken floes at the landfast ice-edge allow a high degree of light penetration which promotes algal growth. In addition, the floes inhibit dispersal of the bloom organisms by wind. If the locale is one where upwelling of nutrients from depth can occur, a highly productive region may result. The location of the ice edge also determines where in the food web the primary influence of production will be directed. When the pack ice is over the Continental Shelf, benthic (seabottom) food webs benefit whereas if its location is over deeper water, production may enter pelagic (oceanic) food chains.

As discussed previously, the Mackenzie River provides inorganic nutrients, heat and sediment to the Beaufort Sea. Within the plume, turbidity limits the penetration of sunlight and thus the process of photosynthesis, in spite of an ample supply of nutrients. The dissolved solids are carried by the Mackenzie current beyond the plume, to its outer edge. Here the sun's energy illuminates the less-turbid water, making the plume edge a potentially productive area. Internal waves generated at the fresh water/salt water interface maintains a well-mixed water column. However, the plume edge is a variable region. It has no defined location nor restraints. Planktonic organisms, subject to vertical and horizontal translocation by winds and waves, can be dispersed and the bloom inhibited by currents.

Profiles of different nutrient concentrations in nearshore and off shore Beaufort Sea waters.

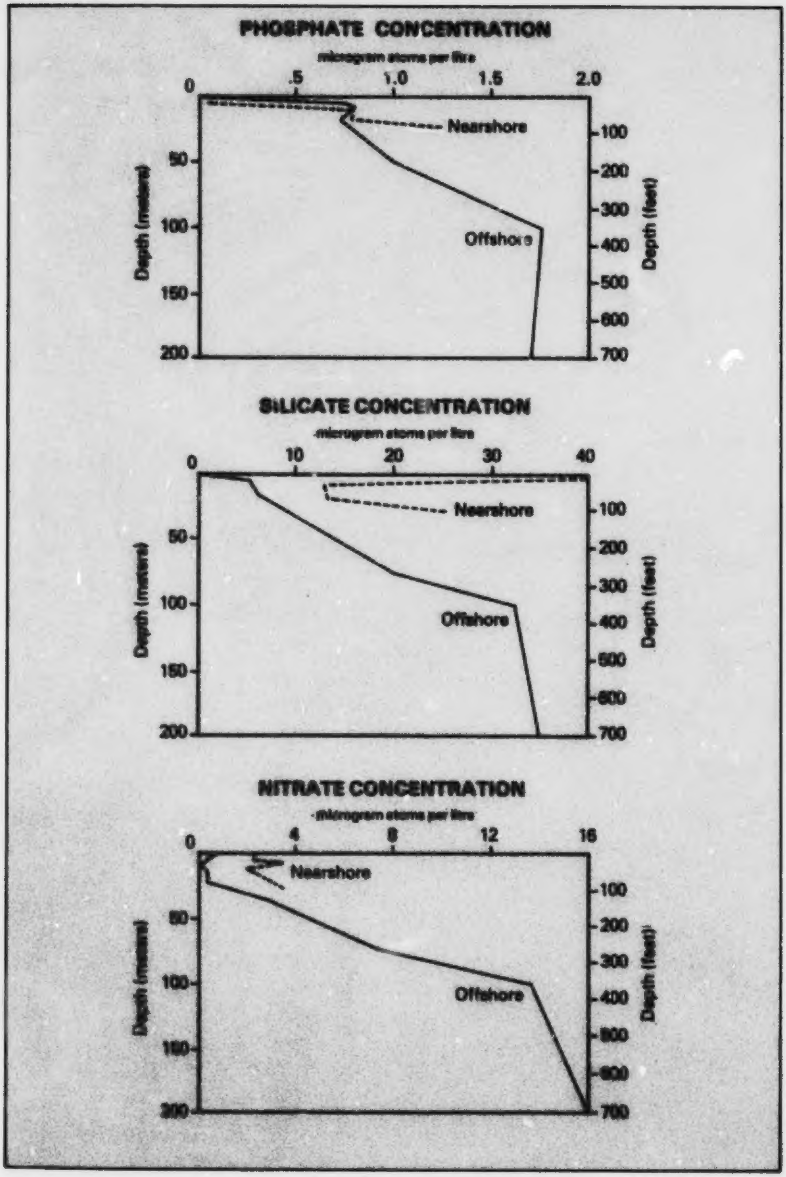
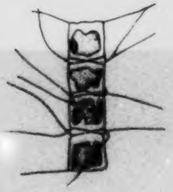


Figure 28



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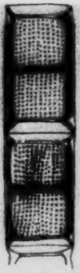

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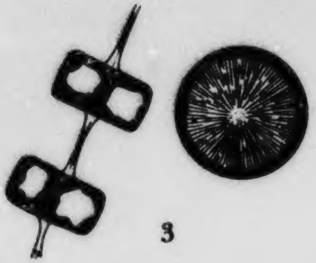

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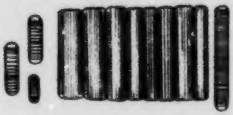

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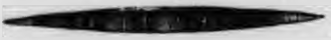
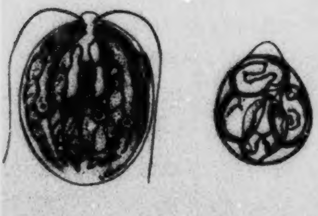


5

Diatoms

1: *Chaetoceros furcellatus* J.W. Bailey
2: *Melosira islandica* O. Müller
3: *Thalassiosira gravida* Cleve
4: *Nitzschia cylindrus* (Grunon) Hasle
5: *Nitzschia seriata* Cleve



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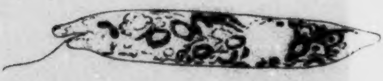
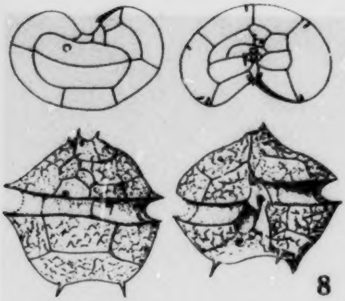


7

Flagellates

6: *Chlamydomonas pulsatilla* Wohlenweber
7: *Euglena* sp.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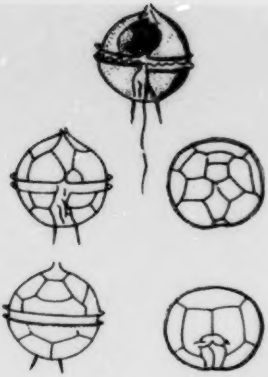
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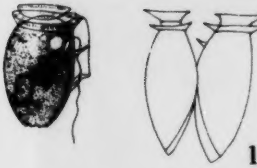
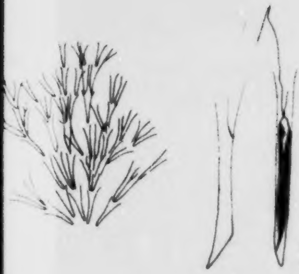

10

Dinoflagellates

8: *Goniaulax catenata* (Levander) Kofoid
9: *Peridinium cerasus* Paulsen
10: *Dinophysis acuminata* Claparede and Lachmann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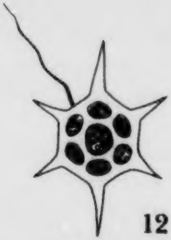
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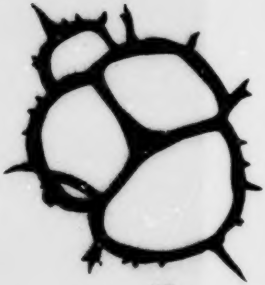
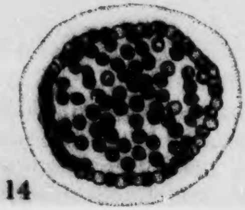

13

Chrysophytes

11: *Dinobryon balticum* (Schuett) Lemmermann
12: *Distephanus speculum* (Ehrenberg) Haeckel
13: *Ebria tripartita* (Schumann) Lemmermann


14

Blue-green Algae

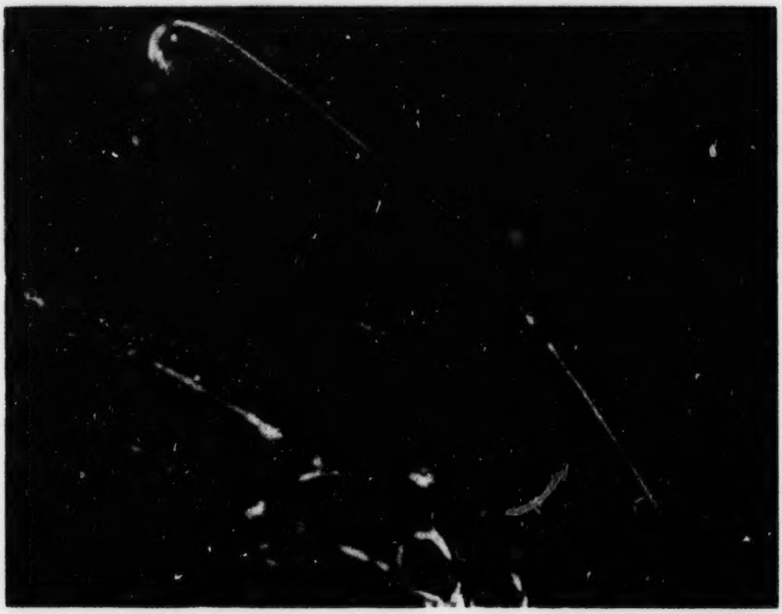
14: *Coelosphaerium* sp.

In winter, sunlight is gone from the Beaufort Sea and photosynthetic activity ceases. It is during this period that inorganic nutrients such as phosphorus, silicon, nitrogen and carbon are replaced (Figure 28). In the growing season these scarce but vital elements are depleted by the phytoplankton. Phosphorus, which exists in ocean waters as phosphate ions, is absorbed by microscopic algae. Silicon is utilized by diatoms and other silicon-secreting organisms. By the end of the brief arctic summer, the nutrients remaining in the water have been reduced to a minimum. Although the regeneration of nutrients is continuous throughout the year, its rate is increased during the warmer seasons. However, the growth demands of phytoplankton during the spring and summer bloom generally exceed the regeneration rate of one or more of the nutrients.

At the first penetration of springtime sunlight through ice and open water, photosynthesis begins and new algal plant growth is found on the bottomside of ice. Populations of diatoms grow and divide on the undersurface and inside the bottom few centimetres of the ice. The algal cells responsible for this under-ice bloom are present in the water during freeze-up. Species tolerant of reduced light conditions (such as diatoms), are able to take advantage of the post-winter, nutrient-rich state of the water and ice. As daylight hours increase, and as leads open up in the offshore pack, other plankton species begin to proliferate in the water column.

Among the techniques used to monitor the progress of an algal bloom are calculation of total cell numbers, or the total amount of chlorophyll, in a given surface area or volume of water. Studies conducted near Point Barrow, Alaska, have shown that growth begins in late February and peaks in May. This early plant growth on the bottom surface of the ice is important to the ecology of arctic marine ecosystems; it extends the growing season and supplies plant material to herbivorous zooplankton that graze on it at an otherwise barren period of the year. The amount contributed to overall primary production by the under-ice populations is a matter of debate. Some scientists believe that up to 30 percent of total photosynthetic production may originate with epontic (undersurface of the ice) life forms.

Of these, the most important are the diatoms, microscopic unicellular plants, some of which form chains. They have shells of translucent silica and come in a great many forms. As well as living under or enclosed in the arctic ice, diatoms are also found floating in water, attached to the bottom, on larger plants, and animals. Diatoms are the major producers in marine plankton. Also represented in the epontic community are the dinoflagellates,



▲ Pennate diatom. *Navicula sp.* in under-ice flora, near oilspill site, Balaena Bay, June 1975.

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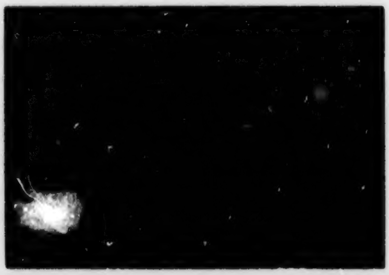
which have whiplike flagella that provide them with a slight degree of locomotion.

Feeding on this algal "crop" are zooplankton and other pelagic invertebrates. These range from single-cell ciliates (hairy surfaces capable of vibratory motion), to nematode (unsegmented) worms

▲ BILL ADAMS

Chrysophyta *Trachyneis* (marine diatom magnification x630) from seawater sample below ice, Balaena Bay, June 1975.



▲ BILL ADAMS

Chrysophyta *Synedra* (marine diatom magnification x630) from seawater sample below ice in Balaena Bay, June 1975.

▲ Amphipod living on bottom surface of the ice. W.A.T.E.R. ASSOCIATES LTD.

and various copepods (tiny crustaceans). Larger invertebrates associated with the arctic ice consist of amphipods (shrimp-like crustaceans), an abundant genus being *Onisimus*. These herbivores, or "grazers", are the second level of the arctic marine food chain.

Amphipods are omnivorous, feeding upon detritus, carrion and algae. They have been collected in bottom sediments, in the water column, and in or on the undersurface of ice. The energy budget of these animals is yet to be fully examined (i.e., the relative importance of foodstuffs to the animal's survival). More significant perhaps than absolute numbers, are observations that have been made with respect to life cycles. Many breeding cycles in nature are timed so that release of the young coincides with a period of food abundance. Juvenile copepods and amphipods have been shown to be present in the epontic community in large numbers. Carnivores benefitting from this production include amphipods such as *Gammaracanthus loricatus* and *Onisimus glacialis*, the arctic cod, ringed seals and seabirds that feed along ice edges.

Nutrients

$$\text{carbon dioxide} + \text{water} + \xrightarrow[\text{light}]{\text{green plants}} \text{organic material} + \text{oxygen}$$

The basic materials necessary for photosynthesis are contained in the above equation. Of these, only the absence of light

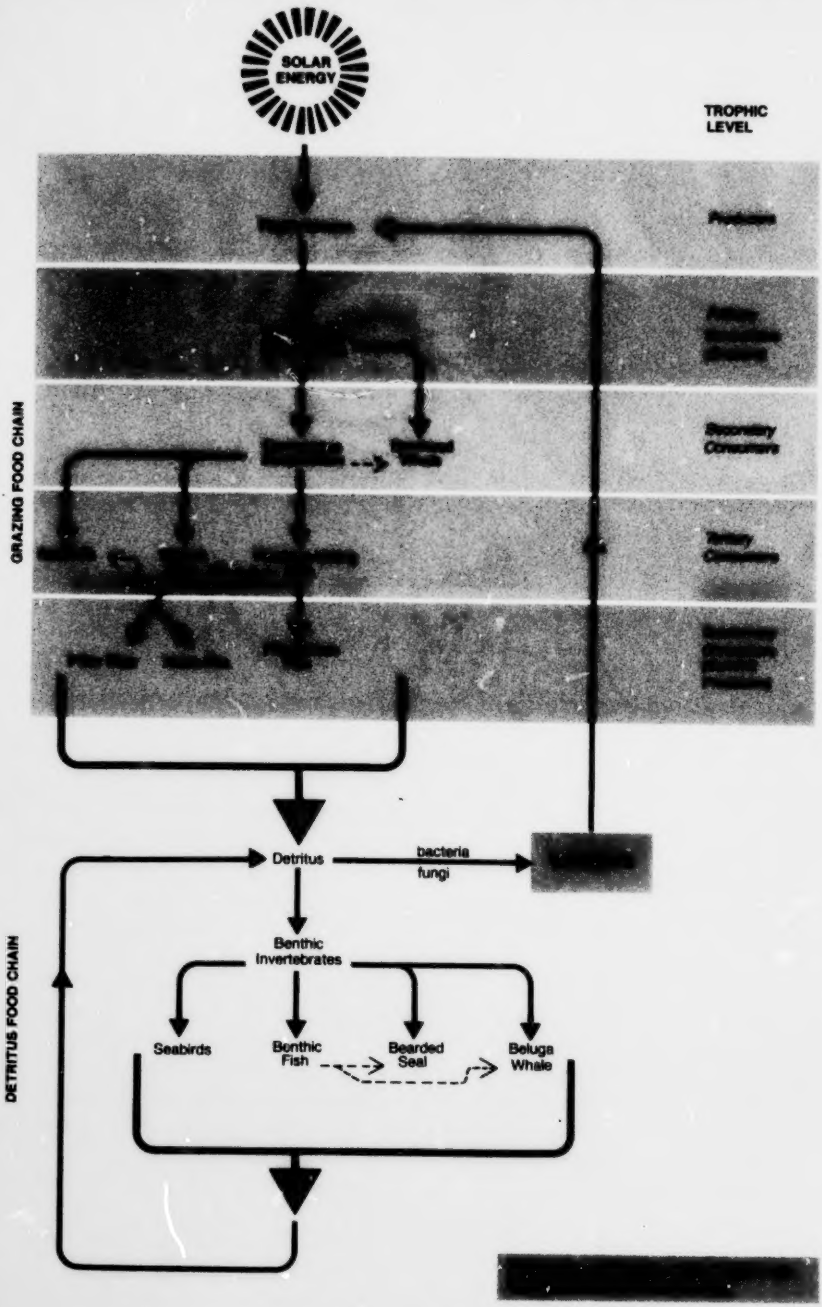

SOLAR ENERGY
TROPHIC LEVEL
Producers
Secondary Consumers
Tertiary Consumers
GRAZING FOOD CHAIN
DETRITUS FOOD CHAIN
Detritus
bacteria
fungi
Benthic Invertebrates
Seabirds
Benthic Fish
Bearded Seal
Beluga Whale

Figure 29

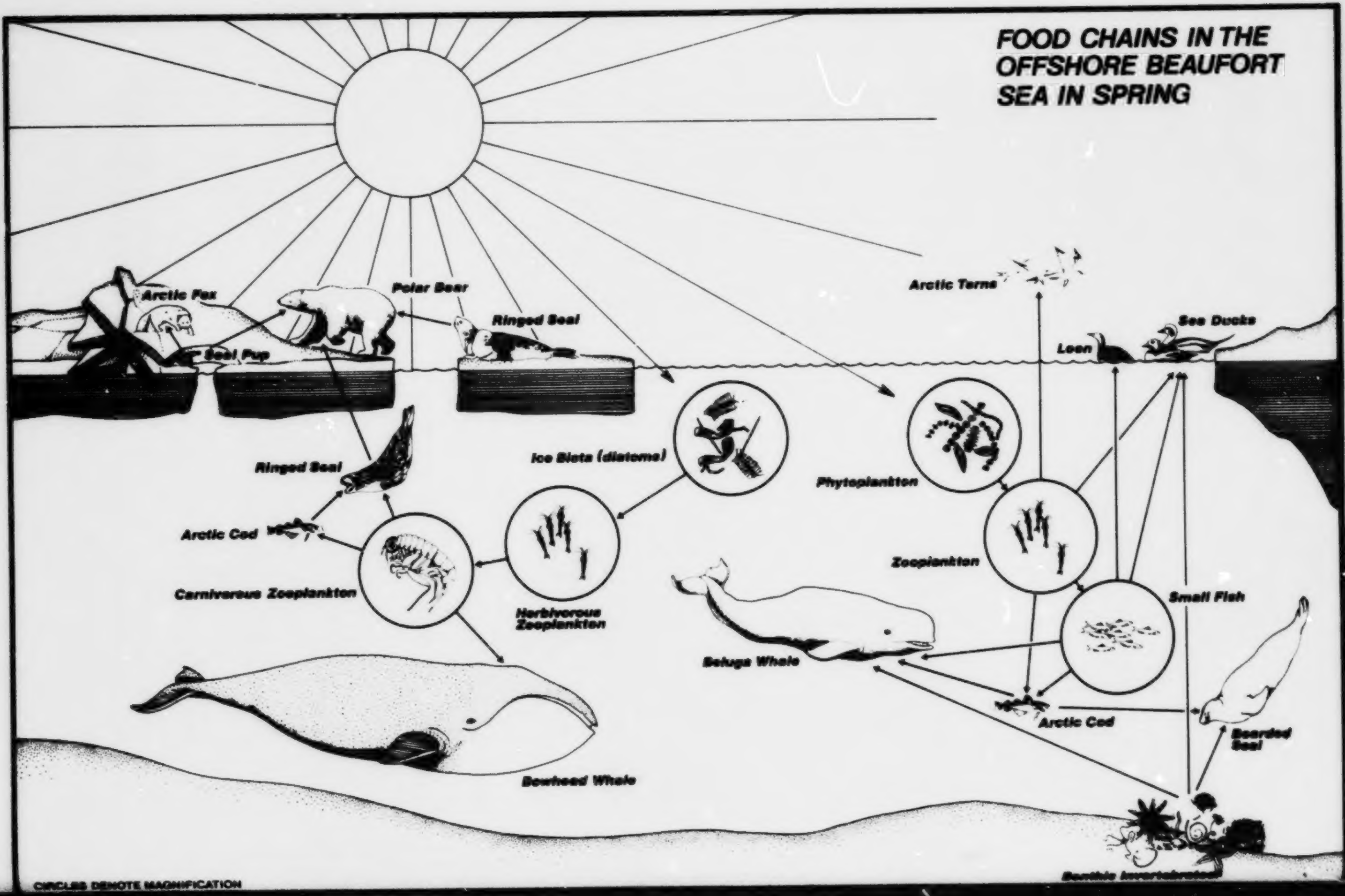
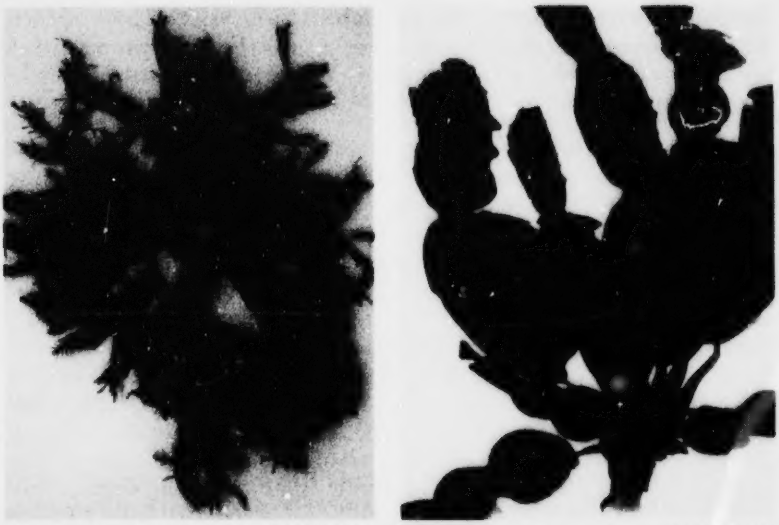

FOOD CHAINS IN THE OFFSHORE BEAUFORT SEA IN SPRING
Arctic Fox
Polar Bear
Ringed Seal
Seal Pup
Arctic Terns
Loon
Sea Ducks
Ice Biota (diatoms)
Phytoplankton
Ringed Seal
Arctic Cod
Herbivorous Zooplankton
Carnivorous Zooplankton
Zooplankton
Small Fish
Beluga Whale
Arctic Cod
Bearded Seal
Bowhead Whale
Benthic Invertebrates
CIRCLES DENOTE MAGNIFICATION

Figure 30



▲ *Phycodrys.* GRAHAM KENT ▲ *Laminaria Saccharina.* GRAHAM KENT

Examples of Beaufort Sea seaweed.

is limiting to plant growth in the sea. The role played by nutrients in photosynthesis is not well understood. Their function is part of the energy transfer — from light energy to biological matter — essential to all cells. The most important compound involved in cellular energy transfer is adenosine triphosphate (ATP). The ATP molecule is composed of adenosine — a nitrogen-containing compound — and three phosphate groups. The high-energy storage is in the last two phosphate bonds.

Nitrogen is one of the most important elements to marine phytoplankton, and its absence is frequently the most limiting. Two forms, nitrate and ammonia, can be utilized. Since ammonia is volatile, and not found in high concentrations, nitrate is the more common form. It is derived primarily through nitrogen fixation by heterotrophic bacteria whose food is produced by other organisms. Planktonic debris raining down from surface waters normally provides the carbon necessary for this fixation.

Phosphorus is the second most essential nutrient which can, by its scarcity, limit the growth of marine phytoplankton. As mentioned, it exists in ocean waters as ions of phosphate. The inorganic form occurs in amounts varying from zero concentrations to over 0.10 mg per liter. It is absorbed by microscopic algae, which either die or are eaten by herbivores. In either instance, by death and decay, phosphorus is returned to the aquatic environment. In the Beaufort Sea, studies have shown that oceanic replacement plays a greater role for phosphorus than for nitrogen and that nitrate is more critical to plant production in surface waters there.

Silicon, utilized as silicate, is an essential nutrient for the formation of the siliceous shells of diatoms. The cell walls become impregnated with silica, finely ridged and lined, like etched glass. The shell structure consists of two nearly equal-sized valves, one of which fits over the other like the lid of a box. The valves are joined by connecting bands. The protoplasm within the shell interacts with the water environment through either a slit or small pores. During reproductive division of the protoplasm, one of the two daughter cells keeps the lid valve while the other retains the box valve. They each then grow a complementary valve to complete the diatom structure.

To summarize: the requirements for primary production in the Beaufort Sea include: light, carbon, nitrate-nitrogen, phosphate-phosphorus, silicate-silicon. All but carbon differ in availability throughout the year, sufficient to affect the growth of phytoplankton.

It is within the euphotic zone (depth to which enough light penetrates to support active photosynthesis), that nutrients become depleted during the summer months. The situation is accentuated by vertical stratification of the water column during late spring and summer. Water from ice melt and river freshet forms a relatively fresh surface layer. Simultaneously, 24-hour sunlight warms the surface water, decreasing the density and thus strengthening the vertical stratification. The thermocline and halocline occur above 20 m (66 ft). Wind and wave motion is often sufficient to maintain a well-mixed layer above this but insufficient to break down the density barrier. Vertical mixing is necessary for the circulation and exchange of nutrients between bottom water, or bottom sediments in shallow regions. A rapid phytoplankton bloom, which depletes the nutrients plus stable stratification of the water column, leads to a crash in productivity.

In late fall and winter, nutrient levels are replenished through mixing and because the rate of regeneration of nutrients exceeds the utilization by plants during these low light periods. Consequently, peak inorganic nutrient levels are often observed below ice in spring, prior to dilution by melt water and increased plant growth. Ranges of nutrient levels measured in the surface waters of the south Beaufort Sea are listed in Table H.

Table H

Nutrient	Concentration (μg at/l)
nitrate-nitrogen	0-10
phosphate-phosphorus	0-1.6
silicate	0-4.5

The higher values are indicative of late-winter/early-spring within the estuary. Silicate levels, however, remain relatively constant throughout the year. Figure 28 illustrates the fact that nutrient concentrations increase with depth.

Primary production in the sea is estimated from measurements of chlorophyll, cell numbers, oxygen produced, and carbon dioxide taken up. Conversions are then applied to derive grams of carbon produced in an area over time. Research has shown the Arctic Ocean to be the least productive of the world's oceans and the south Beaufort Sea to be one of the lowest in the Arctic.

Numbers of zooplankton individuals in a cubic metre of surface water (from Grainger, 1976)

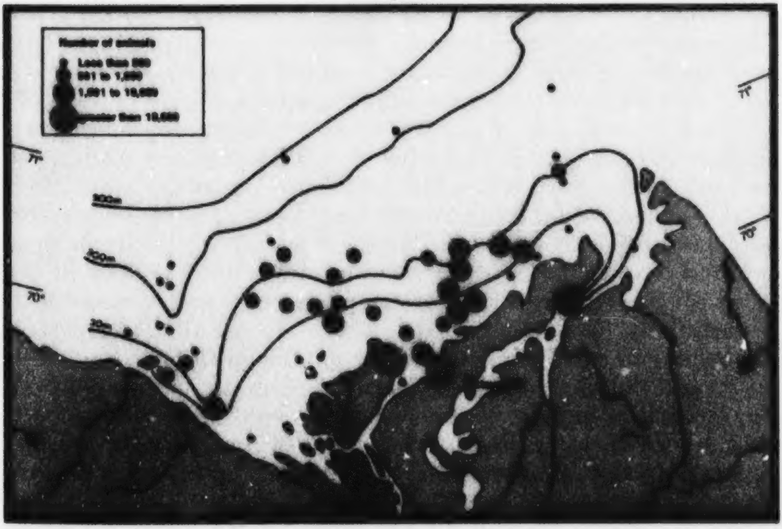

Number of animals
Less than 500
501 to 1,000
1,001 to 10,000
Greater than 10,000
71°
71°
70°
70°
300m
200m
20m

Figure 31

Diversity of zooplankton in the upper 50 metres of the water column
(from Grainger, 1976)

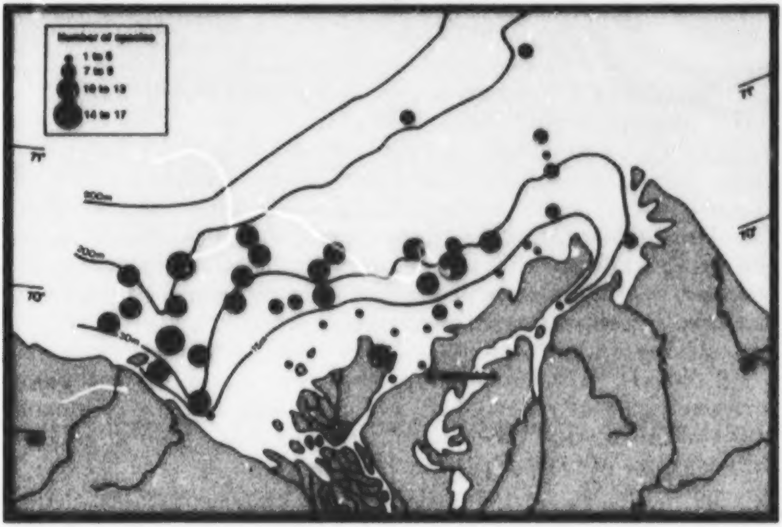


Figure 32

Zooplankton

To date, 92 species of zooplankton have been identified in the southern Beaufort Sea; most common are copepods (40), amphipods (15) and hydrozoans (water animals having a saclike body and a mouth that opens directly into the body cavity) (11) (Table I). Standing stocks are low by world standards and are even small in comparison to Frobisher Bay in the eastern Arctic. For example, during the period late July/early August, roughly 7,000 to 12,000 individual zooplanktors have been recorded in a cubic meter of Frobisher Bay water. Fewer than 5,000 individuals were counted in a similar quantity of water from most stations in the Beaufort Sea (Figure 31). The exceptions were in Liverpool Bay, Tuktoyaktuk harbor and the north coast of Tuktoyaktuk Peninsula, all of which are inshore stations, influenced by fresh water and dominated by few species. For example, in Liverpool Bay, counts as high as 63,000 specimens were measured in each cubic meter of water. Eight-five percent of these were of a single copepod species, *Acartia clausi.* In Tuktoyaktuk harbor a slightly greater percentage of the 49,000 animals collected were *Cyclops.* Offshore stations showed greater diversity of species but fewer individuals (Figure 32).

Table I Zooplankton species from the South Beaufort Sea - (Grainger 1975)

HYDROZOA
Eumedusa birulai (Linko)
Sarsia princeps (Haeckel)
Halitholus cirratus (Hartlaub)
Euphysa flammea (Linko)
Obelia sp.
Melicertum octocostatum (M. Sars)
Tiaropsis multicirrata (M. Sars)
Aglantha digitale (O.F. Müller)
Aeginopsis laurenti (Brandt)
Dimophyes arctica (Chun)
Muggiaea bargmannae (Totton)

ANTHOZOA
Larvae

CTENOPHORA
Beroe cucumis (Fabricius)

NEMATODA
Unidentified

MOLLUSCA
Spiratella helicina (Phipps)
Clione limacina (Phipps)

ANNELIDA
Pelagobia sp.
Polychaete larvae

BRANCHIOPODA
Daphnia sp.
Podon leuckarti (G.O. Sars)
Bosmina sp.

OSTRACODA
Conchoecia borealis maxima
(Brady & Norman)

COPEPODA
Acartia clausi (Giesbrecht)
Acartia longiremis (Lilljeborg)
Chiridius obtusifrons (G.O. Sars)
Derjuginia tolli (Linko)
Gaidius tenuispinus (G.O. Sars)
Calanus cristatus (Krøyer)
Calanus glacialis (Yaschnov)
Calanus hyperboreus (Krøyer)
Limnocalanus macrurus (G.O. Sars)
Diaptomus sp.
Eucalanus bungii bungii (Johnson)
Euchaeta glacialis (Hansen)
Heterorhabdus norvegicus (Boeck)
Metridia longa (Lubbock)
Metridia pacific (Brodsky)
Drepanopus bungei (G.O. Sars)
Microcalanus pygmaeus (G.O. Sars)
Pseudocalanus minutus (Krøyer)
Spinocalanus longicornis (G.O. Sars)
Scaphocalanus brevicornis (G.O. Sars)
Scaphocalanus magnus (Scott)
Scolecithricella minor (Brady)
Epischura sp.
Eurytemora herdmani (Thompson & Scott)
Temorites brevis (G.O. Sars)
Ectinosoma neglectum (G.O. Sars)
Microsetella sp.
Pseudobradya minor (T. and A. Scott)
Harpacticus superflexus (Willey)
Danielssenia stefanssoni (Willey)
Tachidius sp.
Tiske furcata (Baird)
Cyclops sp.
Cyclopina schneideri (Scott)
Mormonilla polaris (G.O. Sars)
Oithona similis (Claus)
Oncaea borealis (G.O. Sars)
Oncaea minuta (Giesbrecht)
Oncaea notopus (Giesbrecht)
Monstrilla sp.

MYSIDACEA
Mysis litoralis (Banner)

CUMACEA
Diastylis rathkei Krøyer)

ISOPODA
Unidentified

AMPHIPODA
Apherusa glacialis (Hansen)
Halirages megalops (Bucholtz)
Gammaracanthus loricatus (Sabine)
Pseudalibrotus glacialis (G.O. Sars)
Monoculodes sp.
Pontoporeia affinis (Lindström)
Aceroides latipes (G.O. Sars)
Acanthostepheia malmgreni (Goës)
Acanthostepheia behringiensis
(Lockington)
Pontogeneia inermis (Krøyer)
Metopa sp.
Hyperia galba (Montagu)
Hyperia medusarum (Müller)
Parathemisto abyssorum (Boeck)
Parathemisto libellula (Lichtenstein)

EUPHAUSIACEA
Thysanoessa inermis (Krøyer)
Thysanoessa raschi (M. Sars)
Thysanoessa longipes (Brandt)

DECAPODA
Sabinea septemcarinata (Sabine)
Pandalus sp.

CIRRIPEDIA
Nauplii
Cypris larvae

CHAETOGNATHA
Eukrohnia hamata (Möbius)
Sagitta elegans (Verrill)
Sagitta maxima (Conant)

COPELATA
Fritillaria borealis (Lohmann)
Oikopleura vanhoeffeni
(Lohmann)

ASCIDIACEA
Larvae

▲ The stinging jellyfish *Cyama capilata,* also widely distributed in North Atlantic. Cape Parry, N.W.T.

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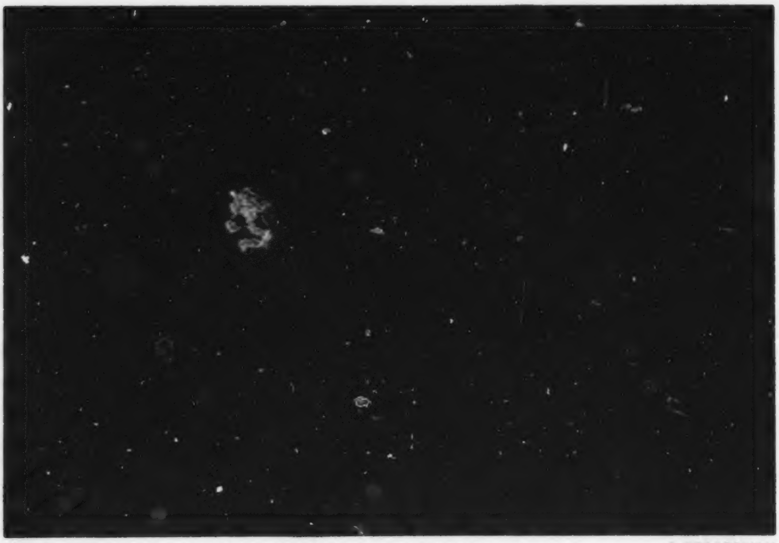
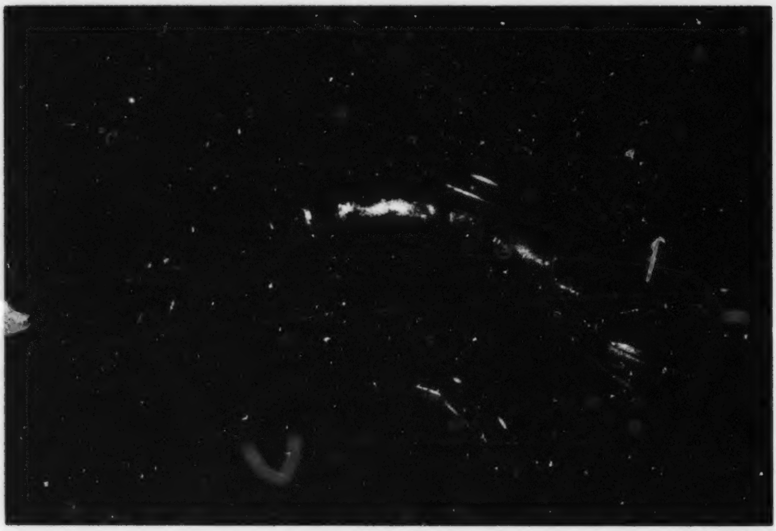


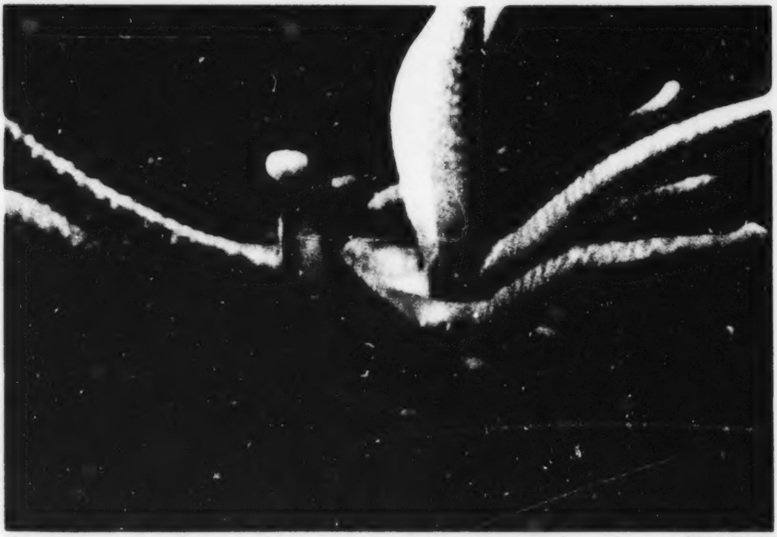
▲ Copepods seen against background of phytoplankton consisting mostly of chain-forming centric diatoms. Cape Parry, N.W.T.

J. HELLEBUST



▲ *Anonyx nugax* caught through ice. Frobisher Bay, N.W.T., March 1981.

JACK FIFE



▲ Sea anenome from sea bottom near oilspill site in Balaena Bay. Abundant at 3-5 m depth. Winter 1975.

J. HELLEBUST

▲ Ice algae. June 1975. BILL ADAMS

The zooplankton of the Beaufort Sea have been classified into broad groups. Shallow inshore areas of low salinity and fluctuating temperatures are characterized by *Acartia clausi, Halitholus cirratus, Limnoclanus macrurus*, and *Derjuginia tolli.* Arctic Ocean surface waters (i.e., the upper 250 m), are characterized by *Aglantha digitale* and *Calanus glacialis.* In the mid-level Atlantic water mass which extends from 250 m to 900 m are found *Chiridius obtusifrons, Gaidus tenuispinus,* and *Heterorhabdus norvegicus.* The Pacific Ocean water that inflows through the Bering Strait to the Beaufort Sea includes species such as *Calanus cristatus, Eucalanus bungii,* and *Metridia pacifica.* The distribution of species corresponds with the different water masses of the Arctic Ocean discussed previously. It also reflects the temperature/salinity tolerances of the individual species.

Plankton living in Beaufort Sea waters may be of river, estuarine or oceanic origin. Freshwater zooplankton found in the Mackenzie River and out into the Delta include *Daphnia* sp. and *Dioptomos* sp. Such species enter the sea with outflowing river water. Estuarine species include *Cyclops* sp. found in a salinity range of 1 $^{o}/oo$ to 12 $^{o}/oo$ and, at the other end of the scale, *Halitholus cirratus* which tolerate 7 $^{o}/oo$ to 20 $^{o}/oo$. Oceanic species are seldom found in salinities below 20 $^{o}/oo$. Arctic surface water species are characterized by *Aglantha digitale* and *Calanus glacialis.* Atlantic water mass species, generally found at depth and in highly saline waters, include *Chiridius obtusifrons* and *Heterorhabdus norvegicus*.

Carried by currents, individuals from any group can encounter salinities and temperatures outside their optimal limits. If the resultant stress is great, the animal may not survive. Invertebrates experience physiological stress during molting periods (due to the exoskeleton, all invertebrates must molt to grow). Similarly, during brooding of young, increased demands are placed on the adult. These natural functions are generally correlated to seasons of abundant food and warmer temperatures. However, the arctic marine environment is not predictable and during periods of physical stress, animals can be pushed beyond their limits of tolerance by natural factors or pollutants.

Marine fishes

Fewer species of fish are present in arctic marine waters than are found in more temperate regions. Half as many, for instance, are found in the whole of the Arctic Ocean as have been recorded along Canada's East Coast. Of the 35 or so marine fish species living in the southern Beaufort Sea, only about a third are common in more northerly waters of the Arctic Ocean. The remaining two-thirds are also found in the Pacific and Atlantic oceans. Many arctic fishes tend to be less specialized: a consequence of the reduced competition for available food.

In cold northern waters, the breeding potential of fish is low. This is largely the result of an abbreviated summer season and slow

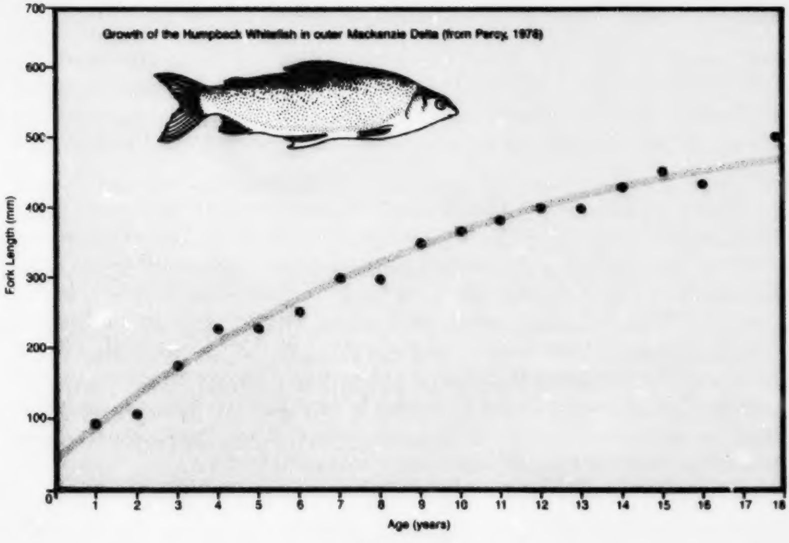


Figure 33

rate of growth. An example of this slow maturation rate is shown in Figure 33 where the age/length relationship is plotted for the humpback whitefish, a species abundant throughout the Mackenzie Delta and nearshore Beaufort Sea. Individual fish mature later and live longer than do their southern relatives; even after attaining sexual maturity some northern fishes (such as Arctic char) do not spawn annually. Eggs and larvae of arctic fishes are large, possibly another adaptation for survival in this rigorous environment.

Some marine fishes in the Beaufort Sea appear to lead a precarious existence, producing a successful spawn only once every several years. This is particularly true for the Greenland cod, Arctic flounder, and a relic species of prickleback found in Tuktoyaktuk harbor. Most other species may be more resilient because of their wide distribution and the large number of year-classes composing a stock. As well, fish stocks of the Beaufort Sea appear much fewer in numbers than those of Frobisher Bay and Lancaster Sound in the eastern Arctic.

Fisheries biologists aboard the research vessels *Pandora* and MV *Theta* carried out a bottom trawling program on the Mackenzie Shelf during the Beaufort Sea Project. Midwater trawls taken in offshore waters yielded a total of 16 species. The catch included larval specimens of cod, sculpins, eelpouts, poachers, snailfishes and sand lances. Unfortunately (for the researchers), adult fish were generally able to avoid the sampling equipment. Midwater trawl catches offshore for the years 1974 and 1975 are compared in Table J. The results dramatize the significant annual variations in the catches and the inferred importance of both the sculpins (cottidea) and the Arctic cod *(Boreogadus saida)*, to the Beaufort Sea marine food web. Much less is known about marine fishes than about either freshwater or anadromous species found nearer the coast.

The Arctic cod is the dominant marine fish found in these northernmost waters. It is common across the Arctic. In Amundsen Gulf, for example, they often comprise 90 percent of the catch in water depths ranging from 65 to 180 m (230-600 ft). In the Beaufort Sea they have most often been taken in mid-water trawls beyond the areas influenced by the Mackenzie River outflow. On occasion they have been caught closer to shore. Arctic cod are small, short-lived fish which feed primarily on copepods, mysids and amphipods. They are believed to spawn during the winter months in the offshore areas covered by ice.

Saffron cod are relatively large (Figure 34), and have also been taken from the nearshore Beaufort Sea. The remains of these fish

Table J
Catch of pelagic fish in mid-water, offshore trawls in the southeastern Beaufort Sea (from Hunter 1977).

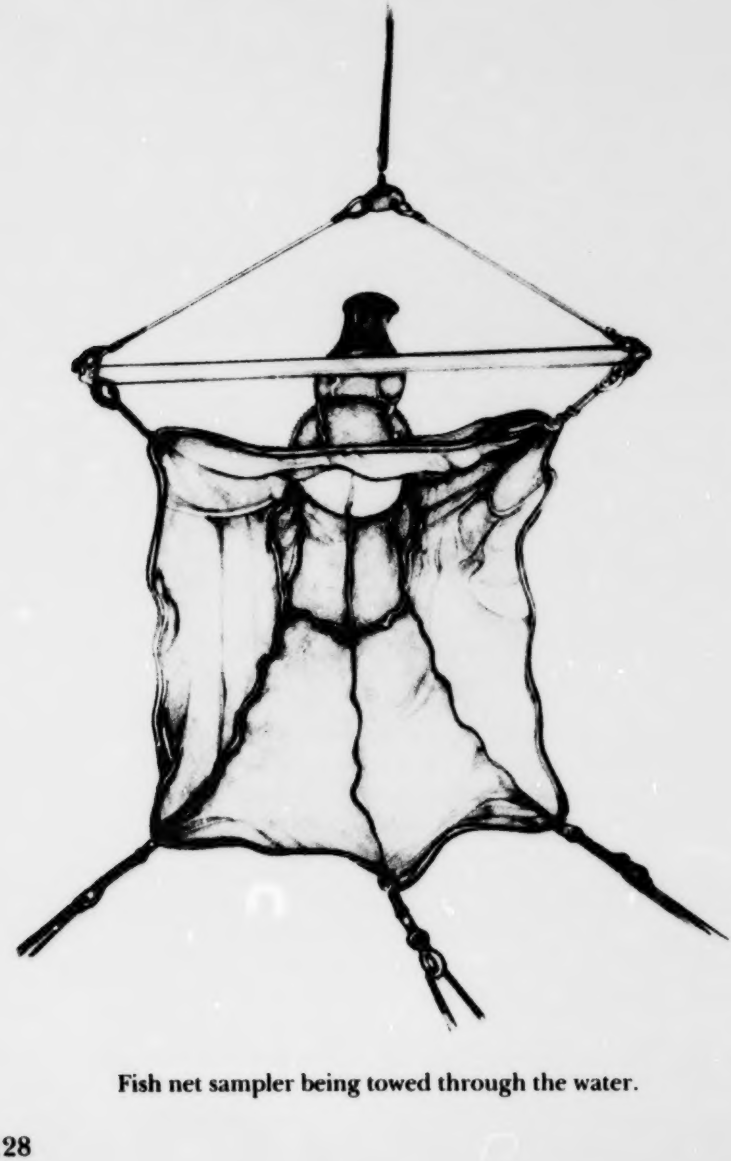
Species		Size of catch (numbers)	
		1974	1975
Arctic cisco	*Coregonus autumnalis*	163	—
Least cisco	*Coregonus sardinella*	39	—
Humpback whitefish	*Coregonus clupeaformis*	1	—
Rainbow smelt	*Osmerus modax*	7	—
Saffron cod	*Eleginus navaga*	19	—
Sand lance	*Ammodytes hexapetus*	1	—
Ninespine stickleback	*Pungitius pungitius*	2	—
Arctic alligatorfish	*Aspidophoriodes olrikii*	—	255
Arctic cod	*Boreogadus saida*	—	4027
Prickleback	(Stichaeidae)	—	111
Eelblenny	*Lumpenus sp.*	—	7
Slender eelblenny	*Lumpenus fabricii*	—	1
Sculpin	(Cottidae)	—	2
Staghorn sculpin	*Gymnoscanthus tricuspis*	—	870
Sculpin	*Icelus sp.*	—	29
Sculpin	*Gymnoscanthus sp.*	—	4
Fourhorn sculpin	*Myoxocephalus quadricornis*	—	2
	Triglops nybelini	—	1
Ribbed sculpin	*Triglops pingelii*	—	24
Snailfish	*Liparis sp.*	—	32
	Liparis cyclostigma	—	40
Bartail snailfish	*Liparis herschelinus*	—	122
	Liparis koefoedi	—	4
	Total	232	5531
	Number of trawl tows	13	22
	Total distance trawled (km)	64	220
	Fish/1000 m^3 (calculated)	1.1	7.5

have often been found in the stomachs of beluga whales. This fact may indicate a substantial offshore population of the species. Saffron cod breed in the offshore and feed on isopods, amphipods, mysids, pelecypods, nematodes and plant materials.

Sculpins are small, bottom-feeding species characteristic of cold northern seas, rivers and lakes. The fourhorn sculpin, a marine species, is most abundant in nearshore waters; it is able to withstand wide variations in salinity. They are also thought to spawn below the sea ice during winter.

Arctic flounder are present in large numbers in Liverpool Bay, Eskimo Lakes, and in smaller numbers along the northeast coast of

Richards Island, as well as in Mallik Bay and in offshore waters near the barrier islands. Their diet includes pelecypods, isopods and amphipods. Specimens taken in the Beaufort Sea appear to mature by their fifth year. Like fourhorn sculpins, they spawn and overwinter beneath the ice.



Fish net sampler being towed through the water.

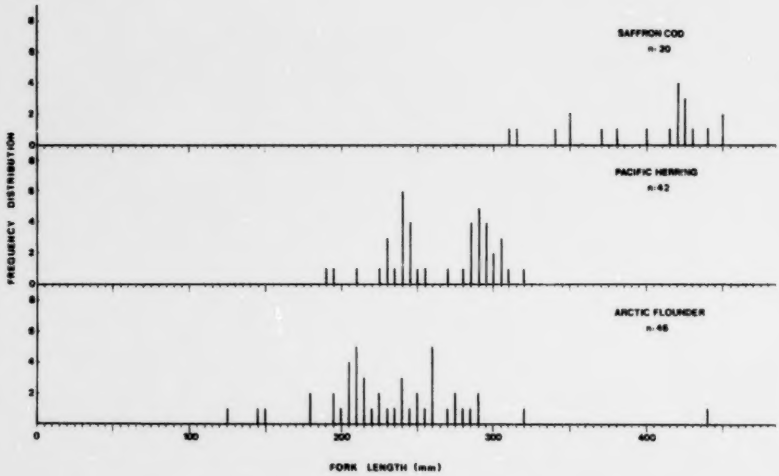


Figure 34: Length/frequency ratio of three marine fishes.

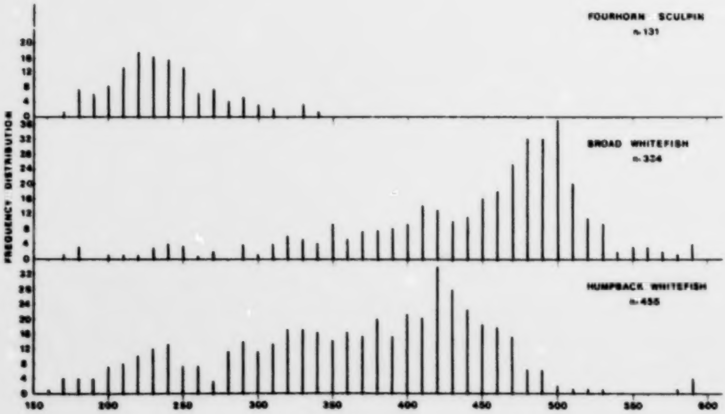
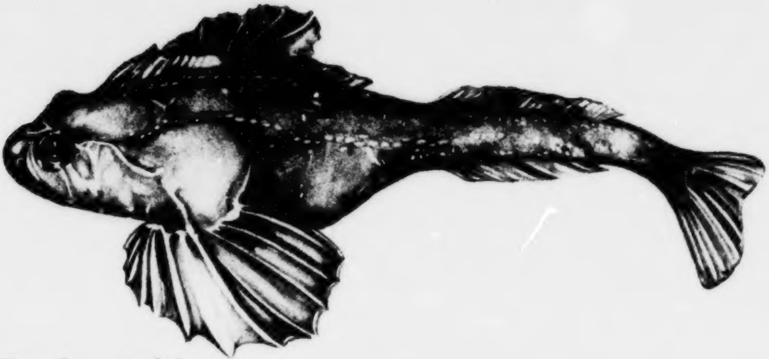
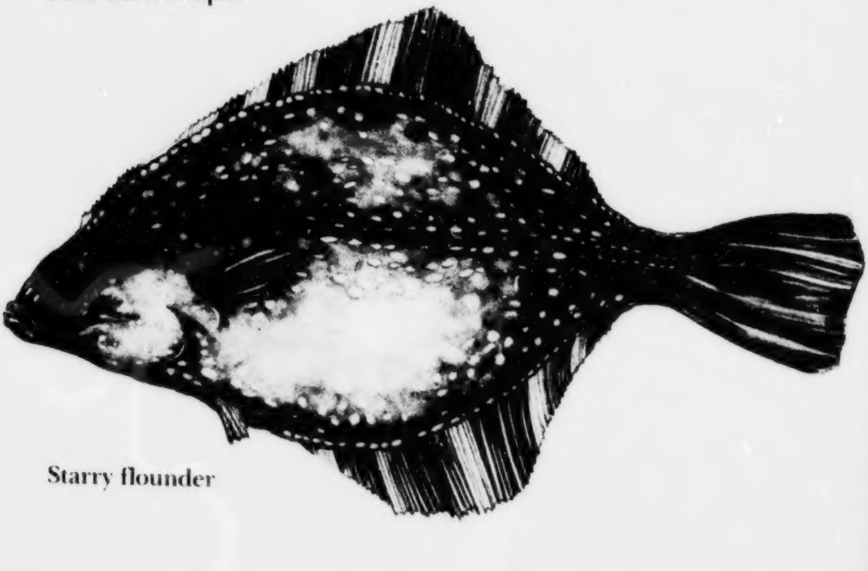


Figure 35: Length/frequency ratio of three coastal fishes.



Four-horn sculpin



Starry flounder

Less common in the Mackenzie Delta region is the starry flounder which has a wider distribution, being found in coastal waters of both the Pacific and Arctic oceans. They have been netted in Tuktoyaktuk harbor as well as at several locations in the outer Delta. They prefer a soft sand or mud substrate, inhabiting waters ranging in depth from the shallow inshore zone to 280 m (900 ft). Flounders appear to migrate only short distances. Adult starry flounders caught in the outer Delta had been eating isopods and plant growth. This species is believed to spawn at rivermouth locations during the winter months.

Pacific herring have been netted in lagoons and bays along the northeast coast of Richards Island and, occasionally, along the Yukon coast. They are more numerous, however, along the Tuktoyaktuk Peninsula, in Liverpool Bay/Eskimo Lakes, and are the predominant species caught in Darnley and Franklin bays. Their diet includes mysids, amphipods and copepods. Sea herring have been fished domestically in the past in the Cape Bathurst area and at Tuktoyaktuk. They congregate in schools near the shore during the winter and spawn in the spring in the shallow brackish waters of coastal bays and river mouths. They normally reach sexual maturity in their sixth year.

Trawl catches by research vessels in Mackenzie Bay and Liverpool Bay have been used by scientists at the Arctic Biological Station, Ste. Anne de Bellevue, Quebec, to prepare rough estimates of local fish populations (Table K). From this data it appears that smelt, sculpin and cod are the most abundant species of fish to be found in the waters farther offshore in the Beaufort Sea during the summer months.

Other scientists have made preliminary calculations of groundfish biomass along the Tuktoyaktuk Peninsula. One such study determined that within a band extending three km from

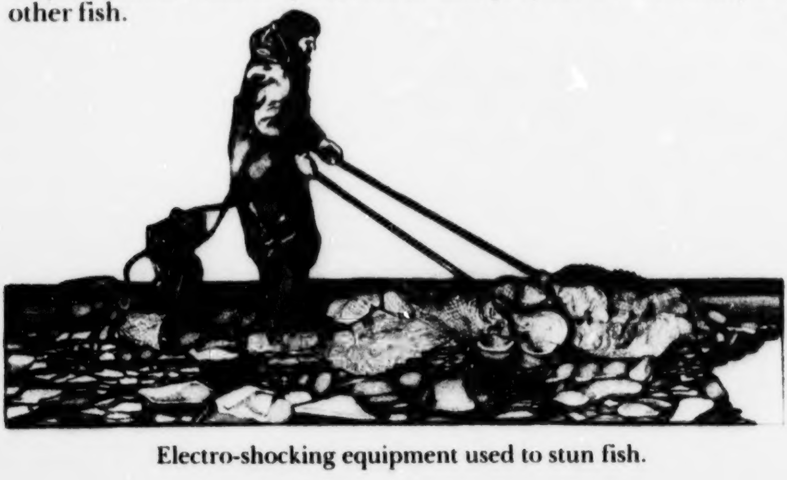
Table K
Population estimates of benthic fish in Mackenzie and Liverpool bays, based on bottom trawl catches (from Hunter 1977).

Species		Number of fish	
		Mackenzie Bay	Liverpool Bay
Arctic sole	*Liopsetta glacialis*	125,000	314,000
Starry flounder	*Platichthys stellatus*	61,000	
Rainbow smelt	*Osmerus mordax*	6,261,000	
Burbot	*Lota lota*	456,000	
Saffron cod	*Eleginus navaga*		73,000
Arctic cod	*Boreogadus saida*		2.300,000
Polar cod	*Arctogadus glacialis*		37,000
Fourhorn sculpin	*Myoxocephalus quadricornis*		573,000
Rough earhook	*Artediellus scaber*		1,406,000
Staghorn sculpin	*Gymnocanthus tricuspis*		14,492,000
Spatulate sculpin	*Icelus spatula*		37,000
Ribbed sculpin	*Triglops pingelii*		221,000
Slender eelblenny	*Lumpenus fabricii*		832,000
Shulupaoluk	*Lycodes jugoricus*		148,000
Pale eelpout	*Lycodes pallidus*		535,000
Fish doctor	*Gymnelis viridis*		128,000

shore, 6 400 kg of fish were present per square kilometer (kg/km^2) of sea bottom. Test fishing offshore saw these values decline to 1 900 kg/km^2. A more recent study has suggested that, at one-half a kilometer from the shoreline, the biomass is 9 500 kg/km^2; at one km it approaches 15 000 kg/km^2; thereafter falling off to 6 000 kg/km^2 at a distance offshore of six km. Such variations in results are not unexpected, given the dynamics of the ecosystem and differences in sampling methodologies.

An unusual phenomenon has been the infrequent appearance in Beaufort Sea waters of capelin, a species associated with more temperate regions. They were observed spawning in large numbers in 1959 and 1960 on the beaches of Herschel Island and again in reduced numbers in subsequent years. Since about 1977 there have been no further reports of this species in the southern Beaufort Sea.

Arctic lamprey, a parasitic species resembling an eel, have sometimes been caught in otter trawls offshore. Arctic char and other species taken in the domestic inshore fishery have been found bearing the scars of lamprey attacks. At an earlier stage of its life the lamprey young, known as ammocoetes, are even more elusive. They live burrowed into the mudflats and stream banks of the Mackenzie Delta, as well as in streams that form the headwaters of this and other rivers. Lamprey ammocoetes are collected for study by the use of electrofishing techniques. At this stage in their life cycle they feed exclusively by filtering large quantities of water and extracting the planktonic organisms. The tiny ammocoetes rarely leave their protective burrows, and then only at night. When they do venture out, they become instant prey for a wide variety of other fish.



Electro-shocking equipment used to stun fish.

Oil in the Sea

Although the Arctic Ocean has not yet been the scene of any major oil spill, the world's more temperate seas have been less fortunate. Scientists have had ample opportunity to study the effects of oil in the marine environment. It is well known that crude oil and petroleum products contain many substances that are deleterious to marine life. In general, crude oil is less immediately toxic than some distilled products but even crude oil that has been weathered at sea for some time still retains some of the acutely toxic hydrocarbons. The more persistent, slowly-acting poisons — such as the carcinogens — are more prevalent in crude oil than in some of its refined derivatives. These poisons are quite resistant to weathering and may remain in the sea and its biological systems for many months following a spill.

None of the presently available clean-up methods can completely prevent or eliminate the biological damage inflicted by oil spills. Thus far, the quick removal of oil by skimmers or by burn-off have been the most successful techniques. The use of detergents and/or sinking agents, on the other hand, causes the toxic and undegraded oil to be spread in the water column. Those procedures can reduce the impacts of surface slicks but the oil remains a threat to sea life. Restoration of contaminated organisms, marshes, and estuarine sediments is virtually impossible, and the return to ecological health is slow.

The federal government is faced with establishing when Canada may need Beaufort Sea oil for domestic use or alternatively, whether to allow the industry to sell it in foreign markets. Yet another decision will have to be made on how arctic oil should be transported: by pipeline south via the Mackenzie Valley or by tankers through the Northwest Passage. If the oil is destined for Japan, the tanker route would be west around Alaska. The environmental consequences will vary depending on the method of transport chosen.

It is generally agreed that, sooner or later, the development of the Mackenzie Delta-southern Beaufort Sea region will move into an oil production phase. The possible sources of hydrocarbon leaks

will multiply to include sub-sea pipelines, offshore oil storage tanks, pumping oil wells and tanker ships plying the Arctic Ocean. Large artificial islands will support drill rigs, producing wells, storage facilities and base camps for workers. Such complexes will generate environmental pollutants in the form of drill muds, sewage and formation water brought to the surface with the oil and gas.

Drilling mud, which is routinely diluted before disposal in the sea, often contains an oil-based emulsifier needed to lubricate the drill-string. Also, vegetable- or oil-based agents are blended into the drilling mud to reduce torque and drag. Since these substances are thoroughly emulsified into the mud system, it is virtually impossible to remove them before the mud is discarded. Another source of unwanted oil is that mixed with the drill-bit cuttings discharged with the mud. Over the period of time that oil will be extracted, the greatest threat to Beaufort Sea life may come from chronic pollution: the sum total of multitudes of minor leaks, spills, and routine discharges of wastes which happen to include toxic chemicals.

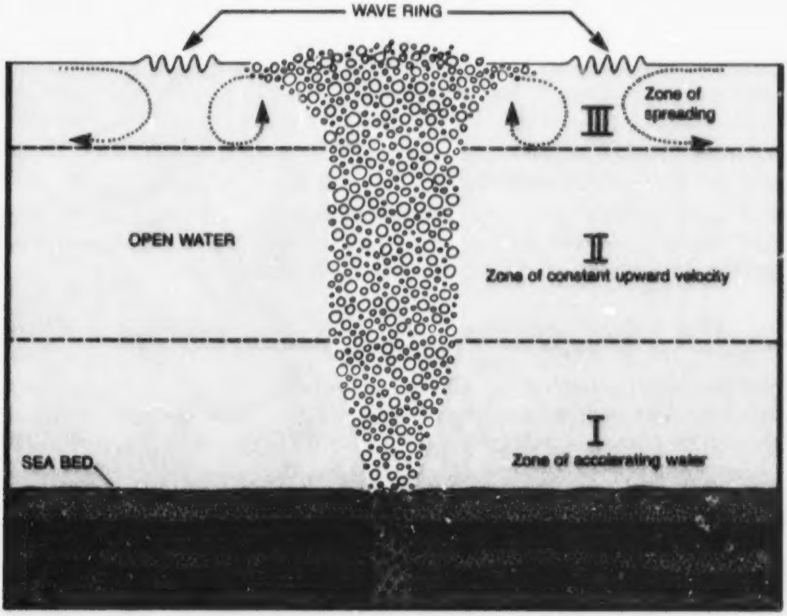


Figure 36: Circulation in seabottom blowout in open water.

Serious accidents where oil is spilled in the Beaufort Sea during exploration, development and transportation of the region's potential reserves would most likely occur as a result of a seafloor oilwell blow-out, a subsea pipeline leak, or a tanker spill. A blow-out would differ from the other two because the oil would probably be released under the pressure of associated gas. The ratio of gas to oil would differ from one well site to another.

Figure 36 depicts a seabottom oilwell blowout. The gas fragments the oil into droplets and sets up a bottom-to-surface current. The oil floats upward, accelerated by the gas bubbles expanding and coming out of solution as pressures decrease. Surface waters then converge and sink in a characteristic circular pattern. A wave ring forms at the interface of gas bubbles and converging surface water. On reaching the top, the oil droplets may coalesce into a slick which will drift away with surface currents.

This description of a subsea oilwell blowout is simplistic, and assumes that there will be no obstructions to flow and no subsurface currents. It also assumes the presence of associated gas under pressure. Oil released under water without any accompanying gas, will also float upwards. The rate at which it flows depends to a large extent on the properties of the oil, its density and viscosity in particular.

One method of identifying crude oils is based on specific gravity and molecular weight. Under this system, crude oils may be classified as light, medium or heavy. The viscosity of oil depends on the temperature. Its ability to flow is also influenced by the types of hydrocarbon chains present and the relative abundance of low molecular weight fractions.

Crude oils contain three classes of hydrocarbons (Figure 37):

paraffins - straight chain, saturated hydrocarbons. Examples: methane, propane, butane.

napthenes or cyclo-paraffins - cyclic, saturated hydrocarbons. Examples: cyclohexane, cyclopentane.

aromatics - cyclic, each carbon atom linked to one neighboring carbon atom by two chemical bands. Examples: benzene, toluene.

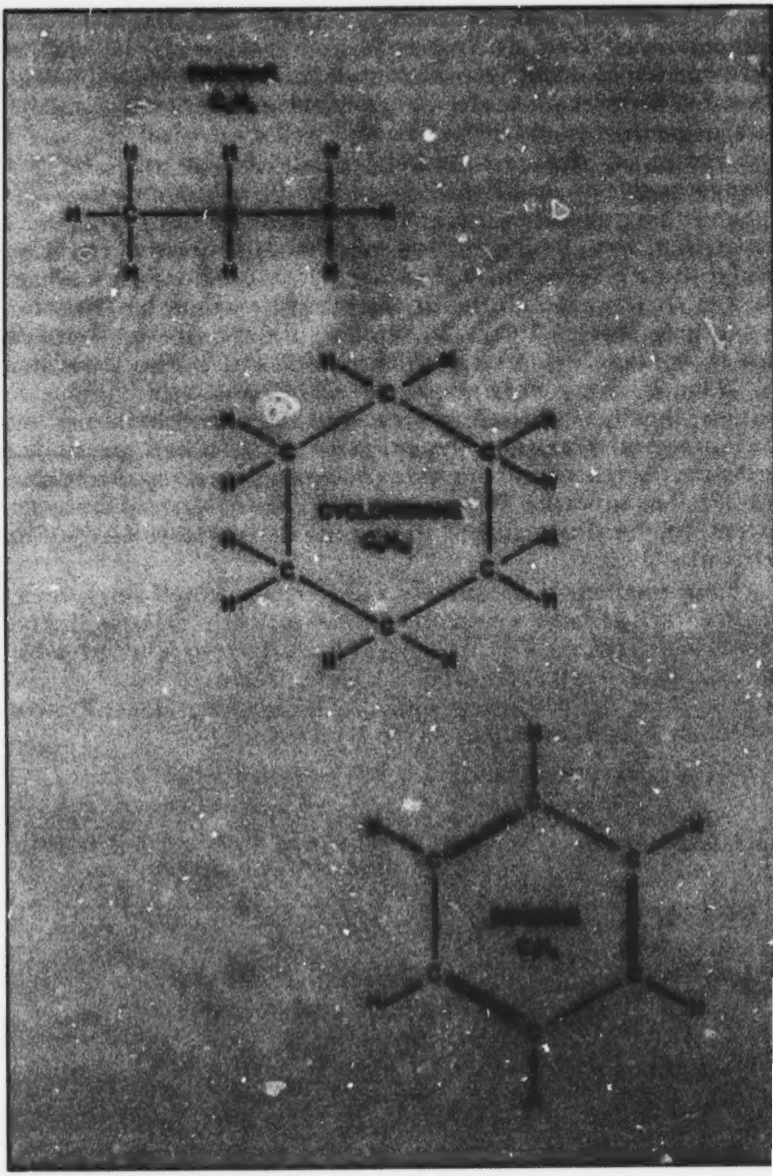


Figure 37: Chemical formulae of hydrocarbons.

The behavior of a crude oil in water, and also its toxicity, depends on the proportion of each of these groups in the mixture. The aromatic compounds are generally more toxic to marine organisms.

Slicks

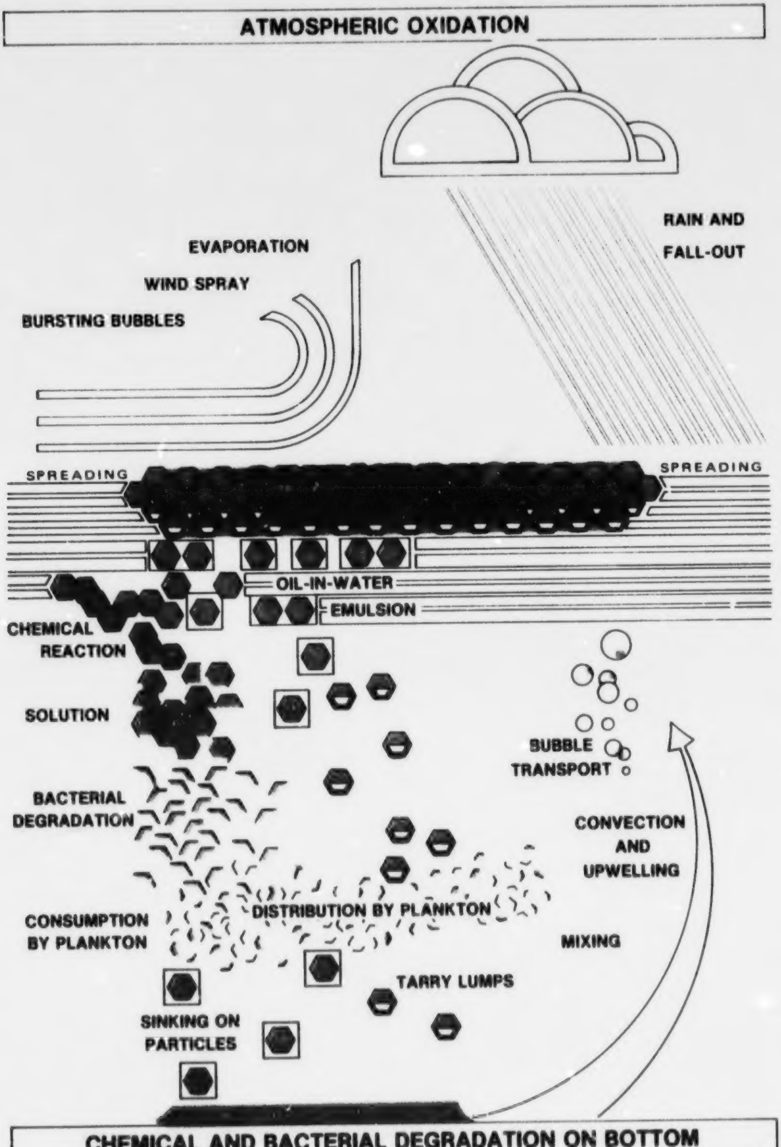
Figure 38 depicts the sequence of events that govern the fate of an oil slick. The relative importance of each will depend upon the properties of the oil, wind strength, temperature, sea currents and wave conditions. With time, the oil is fractionated, its constituent elements disseminated into the air, onto the sea surface, in the water column and bottom sediments.

The thickness of a slick is determined by the pour point of the oil, existing temperature, wind and sea conditions. Pour point is the lowest temperature at which the oil will flow; for crude oil this ranges from -35° to + 10°C. If the temperature of the surrounding water is lower than the pour point, the oil tends to solidify. But if the pour point is lower than the temperature, horizontal spreading of the oil will occur, primarily due to surface tension differences between the oil and water. Gradually, the slick spreads into a thinner layer, aided by prevailing wind and currents.

A slick can be driven downwind at a rate of three percent of the wind speed. The effects of spreading, winds, currents and waves result in the oil drifting away from its source at about 0.5 to 2.0 knots. Generally, the slick will take the form of a thin line, with the inner portions thicker than the edges, rather than a pool of uniform thickness. Slick thicknesses may vary from 0.001 cm to 1.0 cm.

Spreading increases the surface area of the slick which can be acted upon by the environment. Initial processes include evaporation and photolysis (breakdown of oxidation of hydrocarbon molecules), or enzymatic oxidation into alcohols or carbon dioxide. These processes affect the most volatile hydrocarbons which may comprise 25 percent of an oil. At the same time, the aromatic hydrocarbons are dissolving into the water column.

Waves acting on a slick can lead to the formation of an oil-in-water emulsion, where oil droplets become widely dispersed in the water column. The stability of such oil-water mixtures is dependent upon the concentration of asphaltenic components in the crude, as well as oil droplet size. Oil-in-water emulsions tend to be unstable and when the mixing energy ceases (for instance, when the sea becomes calm), the oil droplets often rise to the surface. Some


ATMOSPHERIC OXIDATION
RAIN AND
FALL-OUT
EVAPORATION
WIND SPRAY
BURSTING BUBBLES
SPREADING
SPREADING
OIL-IN-WATER
EMULSION
CHEMICAL
REACTION
SOLUTION
BUBBLE
TRANSPORT
BACTERIAL
DEGRADATION
CONVECTION
AND
UPWELLING
CONSUMPTION
BY PLANKTON
DISTRIBUTION BY PLANKTON
MIXING
TARRY LUMPS
SINKING ON
PARTICLES
CHEMICAL AND BACTERIAL DEGRADATION ON BOTTOM

Natural processes by which oil is degraded in the open ocean. (from Nelson-Smith, 1973)

Figure 38

droplets rise so slowly that they may be thought of as being permanently incorporated in the water column.

The highest oil concentrations are usually found just below a slick and diminish rapidly with increasing depth below the surface. Oil particle size also decreases with depth; a result of the greater buoyancy of large droplets. The dispersal of floating oil is complicated by the fact that the surface slick may be pushed by the prevailing winds in one direction while the soluble fraction and suspended droplets are being carried by subsurface currents in another.

Chemical compounds (known as dispersants) are often used in combating oilspills. They are basically detergents made up of solvents and chemicals called "surfactants". These reduce the surface tension between the water and oil, causing the slick to break down into droplets which spread in a fine cloud through the water column. Dispersants do not remove the oil from the environment, they merely remove it from the sea surface. This has advantages for floating seabirds, but increases the threat to swimming fish and plankton.

Water-in-oil emulsions are a common phenomenon that can be quite stable and incorporate as much as 80 percent sea water. They consist of water droplets surrounded by oil. This semi-solid mixture floating on the sea is often termed "chocolate mousse". Whether an oil-in-water emulsion or water-in-oil emulsion will form during turbulent sea conditions depends on the viscosity and thickness of the oil.

Under some conditions, "sedimentation", or sinking of oil, may become a factor. If the oil that remains after evaporation is denser than the surrounding water, it will sink. Alternately, particulate oil caught in a downward current could become attached to bottom sediment. Sinking will also occur when oil droplets adhere to inorganic sediment or organic detritus. This settling process may be of importance in the Mackenzie Delta where there is a high sediment load. Lighter and, unfortunately, more toxic components are particularly susceptible to absorption into bottom sediments. The affinity of oil for sediment particles is more pronounced in fresh water than salt. Once oil is trapped in this manner and subject to normal sediment transport processes, its impact on zoobenthos and bottom-dwelling fishes may well be greater than if the oil remained as a surface film where it could weather. Oil may persist for extended periods if it is buried in bottom sand before decomposition is complete.

Studies of a simulated oil spill in the open Beaufort Sea show that the motion of any slick that may be produced by accident will be extremely unpredictable: a consequence of unknown and

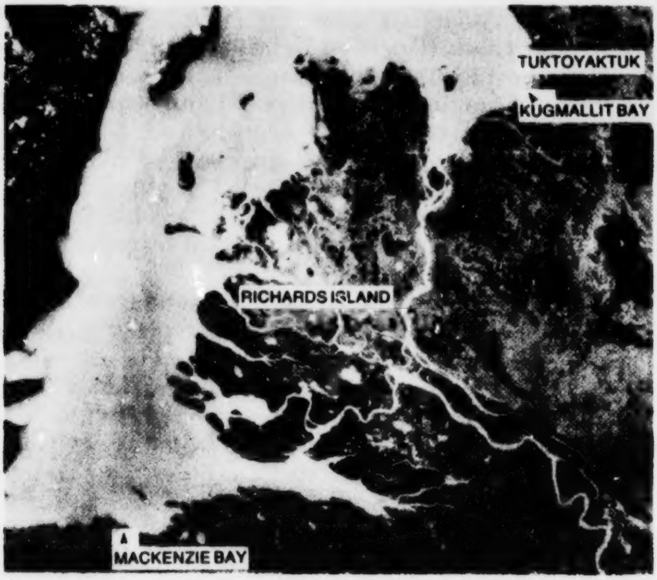

TUKTOYAKTUK
KUGMALLIT BAY
RICHARDS ISLAND
MACKENZIE BAY

Figure 39A: Satellite photo of the Mackenzie River plume, 26 July 1973.

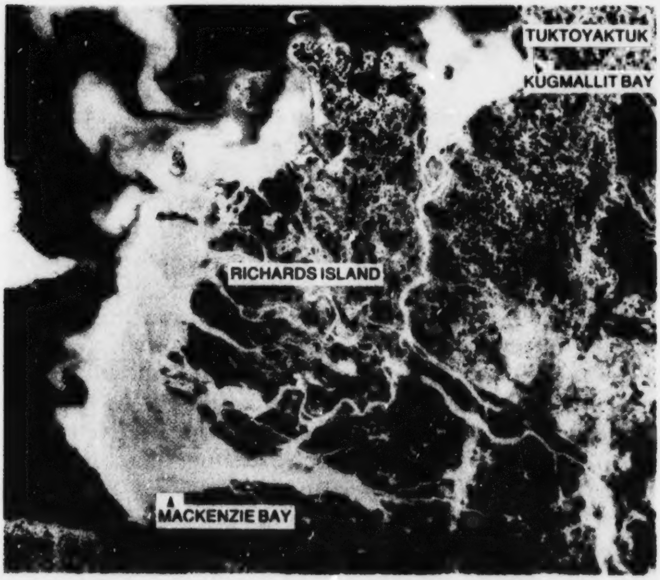

TUKTOYAKTUK
KUGMALLIT BAY
RICHARDS ISLAND
MACKENZIE BAY

Figure 39B: Satellite photo of the Mackenzie River plume, 8 September 1973.

unpredictable currents and winds. For example, the large eddies north of Richards Island and the Tuktoyaktuk Peninsula complicate oilspill trajectory forecasts. These eddies are clearly visible in photographs taken by the Earth Resources Technology Satellite (ERTS) (Figure 39A&B).

In conditions of strong northwest winds, an oil slick could be expected to move first onshore, then skirt the coastline in an easterly direction. Slick speeds of up to 156 km (100 mi) per day are possible. Conversely, winds blowing offshore from the east would hold the oil out at sea. Potentially, it could contaminate the western shores of Kugmallit and Mackenzie bays during its retreat. In any case there would eventually be an onshore movement of any weathered oil which persists in the sea. This might be as floating tar balls which form as the residues of the slick continue to congeal. Tar balls may remain at sea, essentially unchanged, for years before ultimately washing ashore.

Oil in ice

An oilwell blowout or subsea pipeline fracture in winter, from whatever cause, will release oil into water covered with sea ice. Its effect on the marine fishes and invertebrates will, of course, depend on several factors: the flow rate, water and oil temperatures, the depth at which the oil is released, as well as the physical and chemical processes noted earlier. Once released at the sea floor, oil tends to rise to the surface and collect in pockets along the undersurface of the ice rather than forming a stable emulsion. The plume will probably provide sufficient heat to melt an opening in the cover of landfast ice or, alternatively, accumulating gas will cause the ice to fracture. The oil is now free to flow out onto the surface and to be absorbed by the snow.

The experimental oil spill in Balaena Bay, a small and protected embayment on the Beaufort Sea coast (mentioned earlier), has shown that oil that becomes trapped under first-year ice in late fall and winter is quickly incorporated into the growing ice sheet. Once enclosed, it is isolated from weathering and biodegradation processes. Surprisingly, oil recovered more than six months after the spill was almost indistinguishable from fresh crude.

This investigation also established that over the winter the oil migrates up through the brine channels to the ice surface. In spring, the black layer that results readily absorbs heat from the sun, causing premature melting in the contaminated areas. In Balaena Bay, oil-soaked ice melted about two weeks earlier than the adjacent ice sheet.

▲ Aerial of oilspill burnoff site, Balaena Bay, June 1975. BILL ADAMS

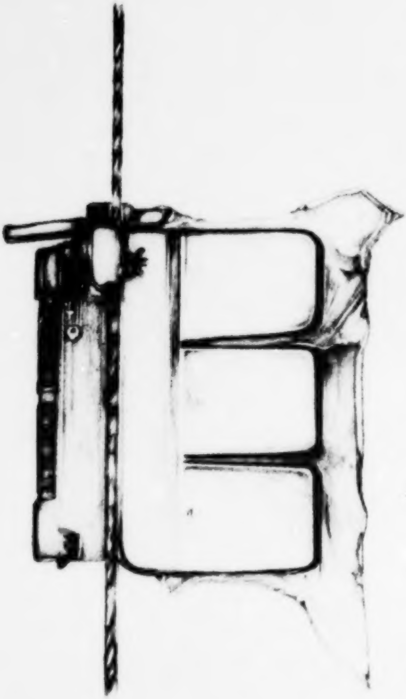
Oil decomposers

Bacteria, among the smallest and simplest of living organisms, play a crucial role in recycling the remains of all plants and animals. Most are "heterotrophs"; that is, microbes that normally derive their food from organic substances. The greatest numbers of heterotrophic bacteria are in the oceans of the world.

Along with yeasts and fungi, certain bacterial strains can oxidize oil residues. In pristine ocean waters, the ratio of these specialized cells to the total bacterial population ranges from one in 100, to one in 10,000. In chronically polluted areas, up to 50 percent may have the ability to break down at least some oil fractions. Abundance of such bacteria is linked to past and present oil pollution. The reason for this is that microbes improve their ability to consume oil over several generations.

The simple alkane fraction of petroleum is more susceptible to attack by bacteria than are the aromatic and napthenic components. Unfortunately, it is the aromatic fraction which is often more poisonous to plankton. In a "typical" crude oil, aromatics comprise about five percent of the total.

Near the surface of the Beaufort Sea, the number of oil-degrading bacteria range from as few as 200 cells per liter, to as many as 100,000. This is similar to other oceans. But higher cell counts are found within the Mackenzie River plume, a fact pointing



Specialized plastic bag used to collect bacteria samples.

to possible upriver pollution and natural oil seeps. Low cell numbers observed within the Eskimo Lakes indicate a more pristine waterbody.

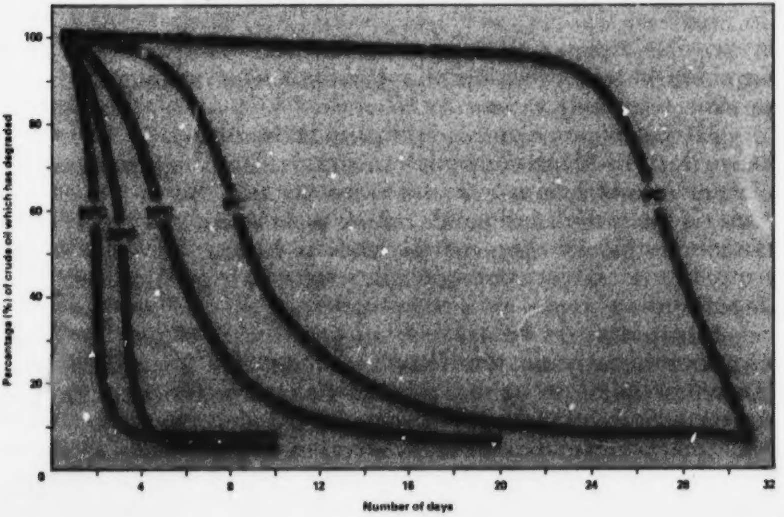
All petroleum compounds contain hydrogen and carbon; hence the term "hydrocarbons". In addition, they may also possess oxygen, sulphur, nitrogen and trace metals. The rate at which bacteria consume oil depends on the type of oil, and the kind of microbes initially present at the pollution source. Water temperature, salinity, oxygen and nutrient availability are also important.

Complete oxidization of oil requires a wide variety of microorganisms, since each can consume only a specific, small portion of the oil. Roughly a third of the carbon content of an oil is converted into bacterial cells during degradation; the remainder is oxidized to carbon dioxide and water. Fluctuations in the numbers of organisms, the carbon dioxide produced, and oxygen used, can therefore provide a means to monitor the rate of breakdown of oils in laboratory experiments.

Research has shown that all bacterial cultures obtained from the southern Beaufort Sea can degrade fresh and weathered crude oil at five degrees C (5°C). When bacteria are cultured at zero degrees C (0°C), a temperature more characteristic of the Beaufort Sea, a two-week incubation period is required. Once started, the biodegradation process is essentially complete within a week. This delay, or lag, permits the bacterial numbers to build up to effective levels. The results of one of the laboratory tests has been summarized in Figure 40; it emphasizes the time lag occurring at lower temperatures.

Although rates of oil breakdown have not been accurately calculated for the Beaufort Sea, they probably approach values observed off Point Barrow, Alaska. There, at the extreme western edge of the Beaufort Sea, about 0.2 micrograms of oil in each liter of water was consumed over a ten-day test period. At warmer temperatures, rates may approach a thousand times this value.

The number of bacteria falls off with increasing depth. In fact, petroleum-oxidizing cells cannot be found on the Beaufort Sea bottom. Those cells which have been isolated from beach sands and nearshore sediments represent contributions from the water column; they are not resident populations. The fact that bacteria are absent from offshore sediments ensures a longer life for pollutants once they sink to the seafloor.



The biodegradation of weathered Norman Wells crude (a northern Canadian oil) using a mixed bacterial culture at different temperatures. (from Bunch and Harland, 1976)

Figure 40

Oil-degrading bacteria require much nitrate and some phosphate. Both these nutrients are normally available in the Beaufort Sea. However, nutrient supply could conceivably prove to be limiting in the event that an oil spill occurred immediately following a phytoplankton bloom. In such a situation, nitrates could be quickly depleted by the competing bacteria and phytoplankton.

Of all the methods of removing oil spilled in the sea, that of biological processes is the slowest but, probably, the most important.

Some effects of oil

A number of physical and biological factors influence the impact that spilled oil will have on the marine environment. They include physical and biological factors such as:

- type and quantity of oil spilled;
- manner of its introduction;
- hydrography of the spill area;
- season of the spill, water temperature, ice cover, etc.;
- weather conditions at the time of the spill;
- methods employed during clean-up;
- species of plant and animal life;
- interaction of oil with biota;
- adaptation to and combined effects of various pollutants.

Because of these variables it is extremely difficult to predict with certainty the biological effects of future oil spills on fishes, benthos or plankton, from either laboratory toxicity tests or from past spills at other locations. We know that the effects will include direct mortality due to smothering, contact poisoning and exposure to toxic components at a distance from the spill site. Indirect mortalities, more difficult to detect, will result from the destruction of food sources upon which higher forms of life depend, and from sublethal behavioral changes.

Even though crude oils differ markedly in their physical properties, it appears that their basic chemical, biological and toxicological characteristics are more similar. They are a complex mixture of hydrocarbons that include alkanes, cycloalkanes and aromatics. Some are extremely volatile while others are relatively stable. It is chiefly the lighter, aromatic fractions in fresh crude that are so highly poisonous to marine organisms.

Heavy crudes are characterized by a high proportion of large hydrocarbon molecules while light crudes feature small molecules. In general, the smaller the molecules the more toxic and more volatile the components. The most toxic effects of an oil spill are experienced in the first few days, before volatile compounds such as the lighter alkanes have evaporated and the soluble aromatics have dissolved out of the slick. It bears repeating that aromatic fractions are highly toxic to marine life; they also can impart disagreeable flavors and odors to fish and shellfish stocks.

The majority of toxicity studies carried out in the past have been short-term. Plants and animals are held in contact with the dilute pollutant for a period ranging from several hours to several days. Such tests can be useful in predicting the immediate impact of an oil spill; however, they fall far short of indicating the degree to which a population or community is damaged over time. Long-term impacts may, in fact, be much more significant. Physiological changes in invertebrates and fishes are not normally observed in short-term toxicity testing since they occur at minute oil concentrations, in the parts per billion and lower parts per million range, and may not be noticeable before lengthy exposure (days/months) to the pollutant. Such subtle effects include changes in rates of metabolism, in feeding and behavior; all of which ultimately affect the growth, reproductive and survival potential of the creature. Sublethal effects can be most dangerous since, while there is minimal damage occuring, these smaller impacts can be cumulative. By then it is often too late to alter the course of events.

Normally, acute toxicity becomes apparent in most species when oil concentrations approach the higher parts per million or parts per thousand range. Toxicity varies with the life stage tested, the technique of applying the pollutant, and even the season when the test is carried out. It is often very difficult to separate the physical effects of oil from its chemical effects in toxicity studies.

Such studies using temperate water plants and animals have revealed a number of important points. For one, it is probably invalid to generalize the results of sensitivity tests farther than the particular species tested, since tolerance to contaminants, including oil, is extremely variable. Within a single species there are usually a few highly sensitive individuals and a few that are very resistant; but the majority succumb to a narrow range of concentrations. Slow rates of reproduction and/or growth, typical for many Beaufort Sea fishes, increase the vulnerability of a species to damage from oil pollution. Also, mortality tends to be greatest where oil is confined in small volumes of water such as shallow nearshore areas; again a predominant feature of the Mackenzie estuary.

Various field and laboratory investigations have shown that, in general, primary production is reduced in the immediate spill area but that recruitment of phytoplankton from adjacent uncontaminated areas occurs rapidly. In the intertidal zone, attached seaweeds are normally resistant to single spills but succumb to chronic or notably heavy oiling. Salt marsh plants are more susceptible to oil. The younger stages of invertebrates and fishes tend to be more sensitive to spilled oil than the adults; these embryonic and larval stages often float in the upper few centimeters of the water column. Burrowing benthic invertebrates are most sensitive to oil; fish are less so and marine plants the least affected. There are, of course, many notable exceptions to such a broad generalization.

The decrease in diversity within the spill area which results from the elimination of some species and proliferation of others may have repercussions farther up the food chain. This will largely depend on the extent and severity of the initial damage. There is insufficient direct evidence yet to conclude that petroleum hydrocarbons are passed up through the food chain in the process known as biomagnification, even though high levels have been observed to accumulate in some marine organisms, fish included, following a polluting incident.

Scientists generally agree that in temperate waters the greatest risk of oiling is in the intertidal zone where beach fauna becomes smothered. Along much of the Arctic coastline, however, repeated ice scouring reduces this intertidal community. Such differences in the physical and biological environment make it dangerous to extrapolate the effects of oil from temperate to arctic waters.

Weathered crude oil appears to neither inhibit nor stimulate the bacteria that are responsible for nitrogen fixation and denitrification; petroleum hydrocarbons cannot be used by them as an energy source. Although fresh crude oil, with its high aromatic content, was found to be toxic, it is unlikely that these bacteria which are found in the sediments along the seafloor would ever come in contact with unweathered crude.

Low concentrations of oil appear to enhance the growth of some phytoplankton species in the Beaufort Sea (especially green-algae), while retarding others (especially diatoms which are prominent members of the ice flora). Usually, oil interferes with the photosynthetic process in phytoplankton, the inhibition increasing with the length of exposure. The larger attached seaweeds are also adversely affected by oil even though they have slime coatings which afford some protection. All the plants tested reacted the same way to Corexit, a chemical dispersant, as they did to oil. At the Balaena Bay experimental oilspill site there appeared to be little disruption and, in fact, slight enhancement of diatom primary production. This apparent contradiction between laboratory-based studies and those done in the field is not surprising since, in the latter cases, regeneration time for phytoplankton is relatively short. Moreover, in Nature, there is nothing to prevent recruitment of individuals from beyond the impacted areas. A large oil spill will, nevertheless, result in a change in the species composition of the community.

The photosynthetic capacity of salt marsh plants and algae is reduced significantly by oiling; in areas of Balaena Bay most heavily oiled, reductions to 90 percent were observed. Apparently, only those plants protruding above the water mark at the time of oiling are visibly affected. Researchers feel that coastal salt marsh areas, which are important feeding sites for birds as well as invertebrates and fishes, are more likely to be permanently damaged than exposed rocky shore areas. (These areas are populated by microscopic algae, many of which overwinter as resistant spores.)

Specific studies

Toxicity tests were carried out on a number of invertebrates native to the Beaufort Sea area. The organisms included: amphipods, isopods, copepods, a jellyfish and a barnacle. For comparison purposes the juvenile stage of a bottom-dwelling fish, the fourhorn sculpin, was also exposed to oil. The relative sensitivities of these ten organisms to oil is summarized in Figure 41. The oil concentrations used in the investigation are relatively high and would only be expected to occur over a small area for a very brief period of time. The results are meant to characterize the worst possible conditions that could be encountered following an oil spill.

In the bioassays, Norman Wells and Venezuelan crude oils appeared to be more toxic than either Atkinson Point or Pembina crudes; however, significant mortalities only occurred at very high concentrations. The least tolerant of the organisms was the jellyfish and the most resistant were the isopods. The short-term impact in a heavily oiled area would be a tendency toward selective elimination of sensitive species, followed by an increase in the abundance of more tolerant forms that are able to take advantage of the reduction in competition and predation. The epifauna (animals that live on the surface of the sea bottom), if they are unable to escape, would be affected almost immediately by contaminants within the water column. Organisms that burrow in the sediments (infauna), on the other hand, would be more drastically affected over the long term. Although natural disruption of benthic communities does result regularly from scouring by dragging ice

Relative toxicity after 96 hour exposure to heavy concentrations (1 ml. in 500 ml. of seawater) of Norman Wells crude oil. (from Percy, 1975)

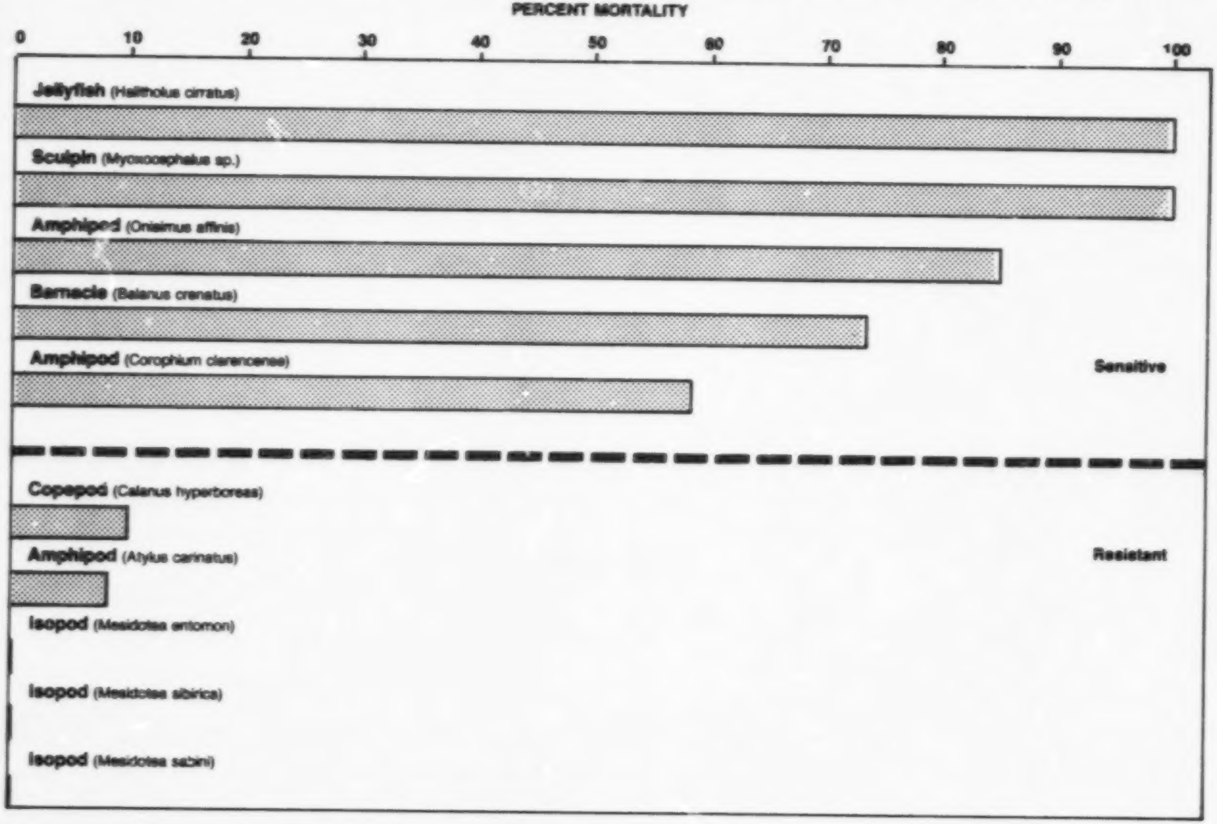


Figure 41

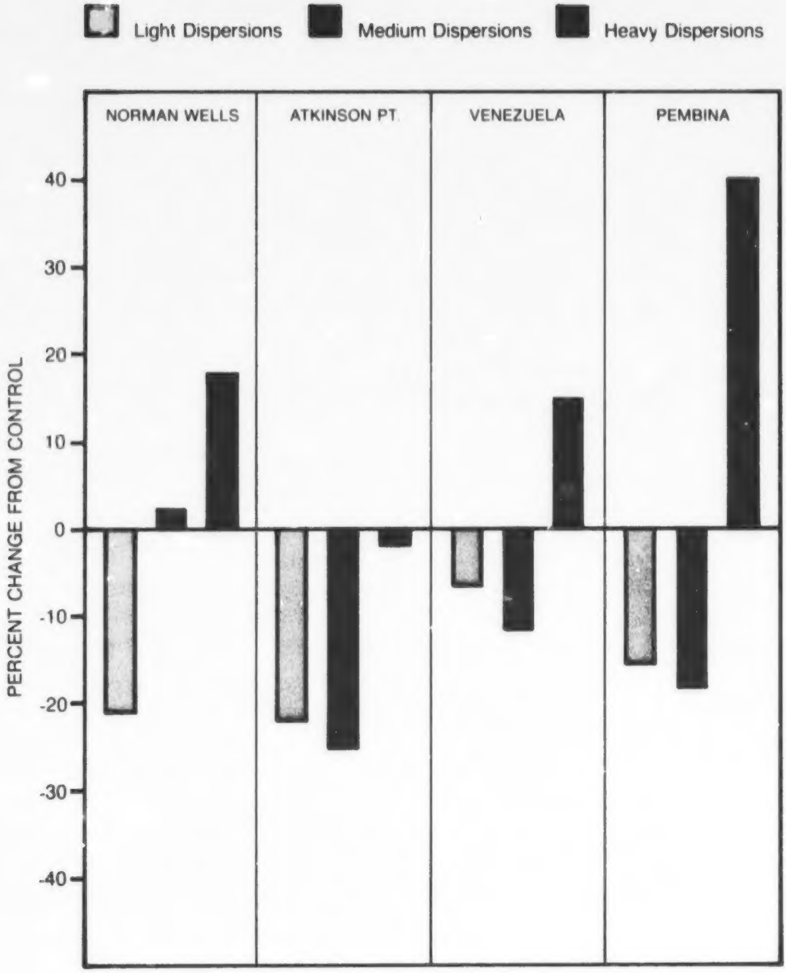


Figure 42: Effect of 24-hour exposure (at 8°C) to light, medium and heavy dispersions of four crude oils on the respiratory metabolism of the amphipod *Onisimus affinis*.

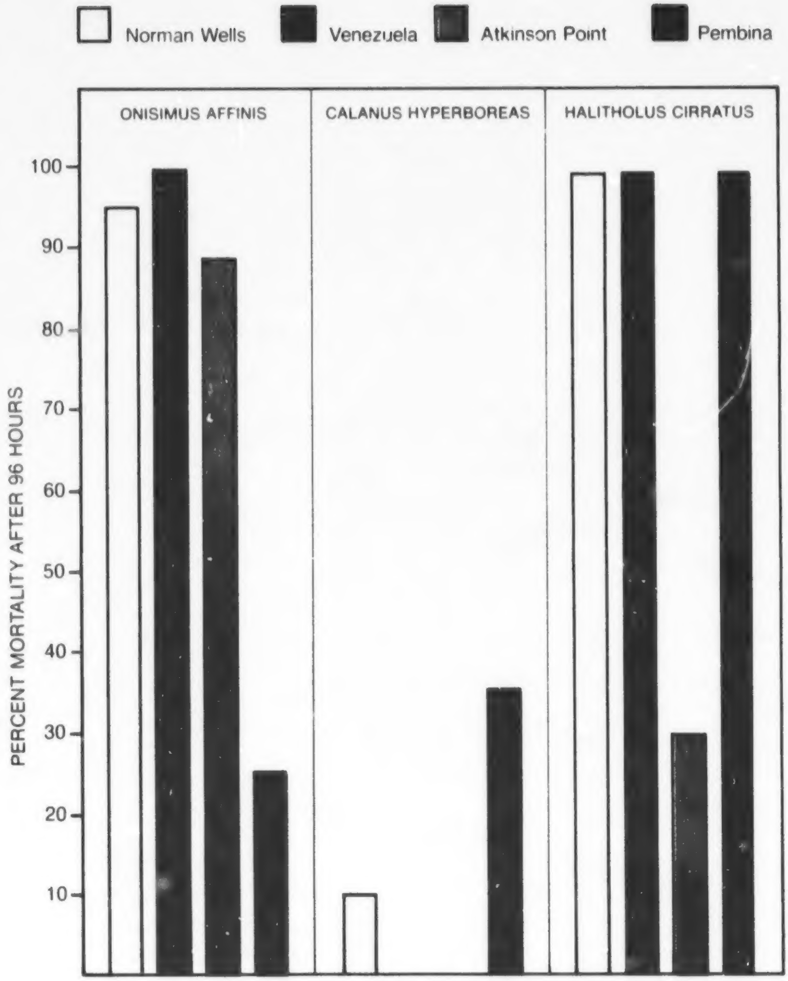


Figure 43: Mortality of three different animals exposed to heavy dispersion of four crude oils, showing relative toxicities.

keels, this cannot be equated to the effects of chemical contamination which can pollute the sediments and prevent their reoccupation for extended periods.

Many invertebrates which can tolerate the seawater soluble components of oil, cannot endure actual contact with heavier fractions. Physical damage occurring during heavy oiling includes impairment of locomotion, feeding and respiration. The most insidious effect, however, is that which modifies the behavior of the animal; for example, how it responds to predators, to oil-tainted food or to oil-tainted sediments. Such sublethal effects can be just as important, if not more so, to the well-being of invertebrate populations.

Arctic crude oils tend to evoke a stronger avoidance reaction among invertebrates than do southern crudes. Isopods, unlike the other test organisms, were generally indifferent to all four oils. The laboratory studies also established that, in emulsion, crude oils can affect the animals' locomotion. At low concentrations this disruption is due to a narcotic effect, whereas at higher levels actual physical impairment occurs. For example, the coordination of pulsations necessary for swimming is lost by the jellyfish after exposure to oil; however, animals subjected to light or medium doses are able to recover once they are removed to clean water.

Norman Wells crude oil tends to impair locomotion more severely than any of the other oils tested. Isopods, true to form, are not adversely affected by intimate contact with any of the oils. The metabolic rate of amphipods, however, is reduced by low concentrations of all four oils. In heavier doses, metabolism is considerably enhanced so that there is a net stimulation effect. Crude oils evoking the greatest inhibitory response at low concentrations appear to have the least stimulating effect on metabolism at high concentrations.

Petroleum-contaminated sediments are acutely toxic to one of the amphipod species, yet another burrowed unharmed in both tainted and untainted substrate. Those animals with a preference for untainted sediments lost their ability to discriminate the contaminant at higher oil concentrations.

The timing of a spill would play an important role in determining its impact on the invertebrate fauna. Although toxic components of oil are readily lost via evaporation in temperate water, in the Arctic there are times when these fractions are retained for extended periods either below, or while entrained in, ice. The under-ice flora, and the zooplankton and pelagic fishes grazing on it, could be affected both by sublethal and lethal effects of oil.

The toxicity of Corexit, commonly recommended for oilspill countermeasures, was also examined. The dispersant by itself appears to be nontoxic to the invertebrates at most concentrations but does tend to depress metabolism at low amounts. Unlike crude oil, it continues the inhibition at higher concentrations. Emulsification of oil with Corexit causes a slight increase in toxicity.

Although there is considerable documentation on the effects of oil on temperate water fishes there is virtually no comparable work in the Arctic. What follows is an attempt to summarize in very general terms the available information.

Oil dispersed throughout the water is more poisonous to marine life than equivalent volumes of oil present as surface slicks, primarily because of the more intimate association of dispersed oil droplets with the organism. Pollutant hydrocarbons are normally assimilated through the gills or from fluids and food within the gut. Even the minute oil droplets accidentally accumulated by filter-feeding zooplankton become readily available to pelagic fishes. Apparently gill tissue with its mucous coating effectively repels small amounts of oil, but it is incapable of accommodating heavy or repeated oiling. Once gills become fouled, both respiration and ion exchange are severely inhibited. Since fish possess no means of self-cleaning this inevitably results in death.

Like the invertebrates, fish are affected by sublethal doses of petroleum. Feeding behavior, growth, reproduction or defense mechanisms may be impaired. Water soluble components from crude oils can induce changes in respiration rates. There is also evidence that pollutants such as oil cause an avoidance reaction which may delay or block annual migration patterns.

In most cases, Beaufort Sea fishes are distributed widely enough to be able to survive, at least as a species, an isolated spill. Most are long-lived and therefore it is unlikely that a single polluting event would destroy all age classes. Many of the marine fish are bottom-dwellers and are unlikely to be adversely affected by an offshore spill unless it is widely dispersed in the water column or becomes incorporated in the sediments. Solution and evaporation of the lighter saturated and aromatic components of oil occur early in the life of a slick. An offshore spill will therefore tend to lose those fractions most toxic to fish before reaching the nearshore zone. Nevertheless, the residual oils could cause substantial mortalities in lagoons and embayments. In relatively enclosed areas such as these, bacterial degradation of oil may cause severe oxygen depletion and the release of poisonous by-products. Direct suffocation may result if the slick also prevents gas exchange at the water surface. Embayments along the Beaufort Sea coast are extremely important nursery and feeding areas, both to anadromous species which spawn upriver as well as to some marine fishes.

The total effect that an oil spill might have on an ecoystem is not yet fully understood and probably never will be, even in the more intensively-studied temperate waters. However, it is known that a spill often leads to a relatively rapid increase in microorganisms such as heterotrophic bacteria and their one-celled protozoan predators. This is primarily due to an increase in the food supply; that is, hydrocarbons for the bacteria and, in turn, bacteria for the protozoans. This artificial imbalance creates a high demand for available nitrogen, phosphorus, and oxygen supplies. It has been estimated, for instance, that about four milligrams (mg) of nitrate are required to oxidize one mg of mineral oil. Thus the oxygen demand created by an oil pollution incident can be significant; in temperate regions one liter of oil may consume the oxygen dissolved in over 400 cubic metres of sea water (at 15°C) in achieving complete degradation. Comparable calculations have not as yet been made in the Arctic.

It is generally agreed that, in the event of a large spill in the Beaufort Sea, immediate mortalities would occur primarily in the vicinity of the accident. The long-term presence of oil in offshore sediments, or entrained in ice, would result in low levels of oil being released into the marine environment, perhaps over a large geographical area. This could have ecological consequences due to sublethal effects.

Unknowns

The world's largest oil deposits have been found under land once covered by ancient seas (such as the Middle East), and beneath the deltas of the Earth's great rivers. Unlike those of more temperate zones, the reservoirs of oil that underlie the Mackenzie Delta are only now being tapped. The reasons for this are both economic and geographic: the cost of finding and then delivering the oil to industrial world markets was far too high. This situation changed abruptly in 1973 when the Oil Producing and Exporting Countries (OPEC) cartel was formed to radically increase the price of oil.

Esso Resources of Canada Limited had been drilling exploratory wells on land in the Mackenzie Delta region since 1964. In 1972 this program was extended to the nearshore waters of the Beaufort Sea using artificial islands as platforms. Esso Resources pioneered both the concept and technology for artificial islands, and has built more than 20 in the past ten years. The first island constructed was in water less than three metres (10 ft) deep. Since then islands have been built in progressively deeper waters. Beyond certain depths, due to the costs of fill, drillships are more economical for exploration drilling.

The materials used to build artificial islands are sand and gravel. Various methods have evolved for delivery to the drill site. In winter, at some sites close to shore, trucks have unloaded fill through holes in the landfast ice. In summer, the underwater mounds are more often built up by dredging the surrounding seafloor or with fill excavated elsewhere and delivered to the site by hopper barge. Depending on the distance the fill must be hauled, the cost of island construction can become excessive. The island built by Esso Resources at Issungnak took two seasons to complete and cost approximately $50 million.

New techniques in both dredging and island construction now permit drilling year-round in much deeper waters. Dome Petroleum built the first caisson-retained island (CRI) in 1981 and named it Tarsuit. Esso Resources sited its first CRI in the summer of 1983 at Kadluk. In addition to the advantage of allowing all-weather, all-season operations, the CRIs can be used more than once. In the openwater season, the ballast water is pumped out and, after the giant steel octagon is refloated, it is towed to the next drilling location.

Another development by Dome Petroleum is the Single Steel Drilling Caisson. Built from one-half of an oil tanker, it is sited on a dredged sand berm by water ballasting and is packed round with gravel to protect against sea ice. When drilling at the site is completed, it can be refloated and moved elsewhere.

More than $1 billion has been spent by the petroleum industry searching for hydrocarbons in the Mackenzie Delta and Beaufort Sea region. From the results obtained thus far, industry officials estimate that total recoverable reserves by the year 2000 may approach 16 billion barrels. This is comparable to the proven reserves in the North Sea oilfields. The oil and gas to be extracted from the land around and under the southern Beaufort Sea may be moved to market by icebreaking tankers, by pipelines, or by a combination of both methods. Any and all of these activities — dredging, base camps, pipeline construction — are certain to have some adverse effects on the marine life.

Production

At present the industry is concentrating on delineating the extent of those reservoirs already located. These include Tarsuit and Issungnak which are in relatively shallow water areas — less than 25 m (82 ft) — and Kopanoar and Koakoak in deeper waters. The number of artificial islands required to chart each subterranean reservoir will vary with the dimensions of the pool. When the decision is made to tap the reservoir, one of the exploration/delineation islands can be enlarged and strengthened. A complete production unit, built in southern Canada, can be towed to and installed on this island.

It is more likely that the shallow-water fields will be the first to be developed. When the deeper-water fields such as Kopanoar and Koakoak are chosen, the production system could be an artificial island that features a ship moorage, oil storage and active wells. Eventually a combination of caissons, platforms, atolls, along with some interconnecting undersea pipelines, may evolve. All of these production/drilling platforms would be self-contained with living accommodation, oil storage, power generators and all support services required for such an operation.

Oil fields located on land or close to shore may be developed in similar ways. Once the reservoir boundaries have been plotted, the installation of production facilities can begin. These will be mounted on gravel pads or pilings to minimize permafrost damage. They may be somewhat smaller than the offshore production facilities because of lesser volumes of oil expected to be found there. The hauling of gravel and the installation of the production units will be done in winter when snow roads are in use.

Oil Transport

A network of feeder seabed pipelines will deliver oil to offshore, nearshore and onshore storage facilities. From there the oil will be delivered to southern markets either by arctic tankers or overland pipeline. The tankers would have to load at an offshore storage island. Oil from land and nearshore fields would be pumped through subsea pipelines to the tanker loading terminal. If the oil is to go via pipeline through the Mackenzie Valley corridor to Norman Wells, offshore production would flow through the seafloor trunk lines to a tank farm at the northern pipeline terminal.

Since fluids from production wells usually consist of crude oil, associated gas and some water, a processing system is needed to separate them. To conserve valuable space on an island, the components of a processing system will be stacked; they will also be integrated with waste management equipment. Each production island will require the means to separate gas and water from the crude oil. But final processing of the oil prior to long-distance transport will probably be done at a central island.

On land, where space requirements are less critical, processing systems may not be as compact. Oil well fluids can be piped from adjacent wells, or groups of wells, to a centralized processing facility. The water that results from separating is known as "produced" water. Under normal conditions it is injected back into the geologic strata. In the early phases of oilfield development in the Beaufort, however, the produced water could be treated and then discharged into the sea.

Oil produced on land will be gathered through numerous small diameter (8 to 24 inch), buried pipelines. It will either go to the northern terminal of the Mackenzie Valley pipeline system, or via a subsea pipeline to an offshore tanker-loading terminal. Since the oil will be at ground temperature, engineers see little threat of permafrost melt. Far more difficult to predict are the possible problems with seabottom pipelines. In places they may be buried in sediments that are mostly ice and highly unstable. These ice-rich soils exist at eroding shorelines where the pipeline may have to be laid. The dragging keels of ice floes might also damage the submerged pipe; at a time of year when it would be impossible for divers to repair it.

Mackenzie Valley pipeline

The decision to move Beaufort Sea oil south to Edmonton by pipeline would bring on a whole new set of environmental concerns. The proposal is to build a large diameter (36 or 42-inch) pipeline from Richards Island in the Mackenzie Delta to Alberta, a distance of 2 200 km (1,350 mi). Thanks to the experience gained by the industry during the construction of the Alyeska Pipeline across Alaska, and the Mackenzie Valley oil line south of Norman Wells, no major engineering problems are anticipated building a similar one along the northern segment of the Mackenzie Valley corridor. The right of way will require a ribbon of cleared land 37 m (40 yards) wide to permit the operation of trenching and pipe-laying equipment.

Only about a third of the total length of pipe would be buried. Due to the permafrost which is distributed along the proposed pipeline route from the Delta to the Peace River in northern Alberta, most of it would be built above ground. As with the Alyeska case, the pipe would be mounted on vertical supports. "Cryoanchors" — metal tubes containing gaseous ammonia — are used to conduct heat from the ground whenever the soil temperature exceeds that of the air. As the construction proceeds and the machinery moves forward, cleanup crews will follow to restore and reseed the land.

The disturbance to wildlife by the pipeline may be minimal but the access provided by roads needed during the construction phase allows hunters to exert additional pressures on the animal populations. Construction workers, who are transient in the region but determined to exercise their rights to recreation, may hunt indiscriminately. Even after the pipe has been laid and the workers gone, the network of access roads will remain making it easy for both native northerners and tourists using all-terrain vehicles to hunt the diminishing stocks.

Freshwater fish populations in the Mackenzie Valley are also threatened by the pipeline. The danger is concentrated in the construction phase when increased siltation, caused by dredging, can clog the gills of adult fish, bury their eggs, or smother the emergent larvae.

The proposed pipeline that is to bring Beaufort Sea oil south must cross six major rivers: the East Channel (in the Delta), the Great Bear, the Mackenzie near Fort Simpson, the Peace, the Athabasca, and the North Saskatchewan. At these points the pipeline will be buried in the river beds.

The need for gravel and rock for construction in areas of permafrost is enormous. In the Far North, above the tree line, it presents little problem since suitable materials are easy to locate. But throughout the Mackenzie Valley finding accessible aggregate is difficult. And where it is found, roads to haul it have to be built. Until now, the most common source for construction gravel in the North has been riverbeds. Given the need for massive amounts of gravel — roads, airstrips, pumping stations, compressor sites, and staging areas all require it — the spawning beds of many fish could disappear if the practice continues.

Land use

Seaports, coastal bases, pipeline shore-crossings, tank farms, support camps, roads and quarries will be needed for ongoing exploration and production of hydrocarbons in the Mackenzie Delta-Tuktoyaktuk Peninsula regions. A corridor along the Mackenzie Valley will have to be set aside for a pipeline right of way. Shallow, medium and deep-draft harbors should be designated for industry use. Although the total amount of acreage needed for transport corridors, processing plants and terminal facilities is minimal, decisions concerning land use have yet to be made.

Since petroleum discoveries in the southern Beaufort Sea area have not yet reached the stage of commercial viability, the industry does not know exactly where coastal bases will be needed. Meanwhile, native land-claim negotiations with federal and territorial governments continue. It is not at all clear how the need for oil industry coastal bases will be reconciled with native land claims and federal plans for national parks and wilderness preserves.

At present Dome Petroleum, Gulf, and Esso Resources have major bases at Tuktoyaktuk. The companies foresee the need to expand these bases and Dome plans to develop its McKinley Bay winter mooring site as a harbor with docks, warehousing and personnel accommodation. Gulf is considering another major support base to be built along the Yukon coast, possibly at Stokes Point. This general area is considered ideal for site development since it is close to a rocky quarry and to offshore locales where artificial islands will be built. Both sites may be developed if Gulf succeeds in bringing in an offshore field here.

The proximity of quarries and gravel pits is important because of the significant amounts of fill required as foundation material. Nearly every structure has to be underlain by a gravel pad: drilling equipment, processing plants and tank farms are examples. Airstrips require prodigious amounts of rock and gravel, as do harbor installations and the all-weather road needed to connect the new shorebases with the Dempster Highway.

Surface mining for rock fill is expected to have little adverse environmental effect. Of more concern is the dredging of seabottom sediments both for deepening harbors and for building artificial islands. At risk are the benthic communities of plant and animal life which exist on the seafloor and form essential links in the marine food web. Since millions of tonnes of dredged fill are needed for the scores of exploration islands anticipated as being necessary to find and then develop all the hydrocarbon deposits in the southern Beaufort Sea, the damage to marine ecosystems could well be serious.

Research gaps

Events of the past decade have superseded the effort that went into attempting to understand the ecosystems of the Beaufort Sea. The available scientific resources have been diverted to "crash" programs of environmental research to support the applications of industrial groups wishing to transport oil and gas by ship through the Arctic Archipelago; sink wells in Davis Strait; and mine high-grade zinc ore on Little Cornwallis Island. The major development thrust, however, continues to be the hunt for petroleum reserves. Exploratory drilling is still underway in the southern Beaufort Sea region (and elsewhere in the Arctic). Unfortunately, some ecological problems inherent in the production phase — when the oil and gas is being tapped — are being set aside as problems to be solved *after* reserves in the oil field have been fully delineated.

The bulk of research done since the Beaufort Sea Project concluded is site-specific and financed by the companies. The problem with this kind of research is that as good and as thorough as it may be, its duration is short and it is limited in scope. It is not suited for long-term planning by governments. Even more serious is a growing inability of federal government scientists to adequately assess the value of the information presented with industrial applications. This is a result of the government's policy to downgrade federal scientific institutions in favor of research and development in the private sector. Lacking adequate in-house scientific expertise to evaluate industry's impact assessment documents, government administrators must nevertheless proceed with decisions crucial to the well-being of northern residents, flora and fauna.

Some of the baseline data that was collected under the aegis of the Beaufort Sea Project should be kept up. Critical information gaps exist; they need to be identified and both specific and long-term research programs designed to provide the answers. The results would have practical applications in all phases of northern development; not just exploration drilling. Monitoring studies will facilitate the identification and resolution of potentially dangerous environmental problems at the earliest possible stage. It is important that studies be carried out prior to development, during the period of disturbance and afterward in an assessment phase. It is sometimes crucial to monitor control areas that border impact areas to clarify natural environmental trends.

Immediate needs

A detailed examination of the sea-ice biota is necessary to establish its contribution to annual production in arctic waters. Virtually nothing is known about the habits and habitats of overwintering fish and invertebrates or those living under the polar pack. Such fish may depend to a large extent on the readily accessible sea-ice flora and fauna for their continued survival. Marine fishes have not received the attention they deserve since most fisheries research has been concentrated in coastal waters. The few trawling operations undertaken offshore in the Beaufort Sea have been selective for larval rather than adult fish. Preliminary biomass values have been estimated for both invertebrates and plants but are essentially lacking for marine fish.

It is extremely important to delineate further those areas where critical marine and brackish-water life forms congregate so that contingency plans for the protection of such areas can be drawn up. Through baseline studies we have become familiar with the plants and animals living in such protected embayments as Mason Bay but the ecological processes that occur there remain unclear.

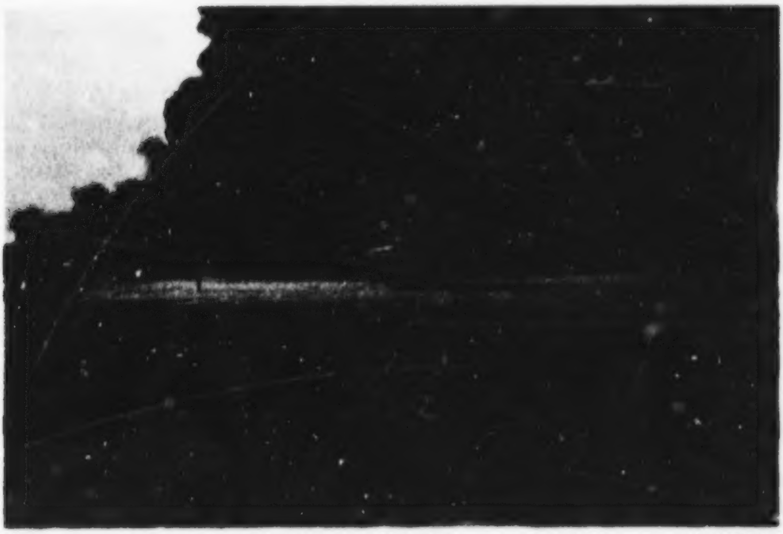
It is obvious that much of today's pollution detection and clean-up technology is not capable of coping with either the climatic conditions or the large volumes of pollutants liable to be associated with exploration, construction and production in far northern areas. For example, in the event of an oil spill — from whatever cause — do we use dispersants as a "clean-up" technique for these productive embayments? For salt marshes? River deltas? These questions require our immediate attention.

Long-term

Baseline monitoring of annual primary production as it relates to the vagaries of the arctic climate must be undertaken. Similarly, annual variations in the distribution and migration patterns of anadromous fish cannot be fully analyzed in a two-year investigation.

Baseline petroleum hydrocarbon levels have been established for a very few plant and animal species. This program should be expanded to provide adequate reference material with which to compare hydrocarbons found in tissues, sediments and water. Such information would be particularly useful in determining the persistence of oil in the arctic marine environment and to trace the pathways and fate of pollutants in the food web. It will be necessary to keep track of the indigenous as well as pollutant hydrocarbons in the Beaufort Sea area.

There are marked differences between the offshore and the inshore; some of these have been discussed earlier. Physical characteristics of landfast ice and that in the shear zone are distinct from those of the polar pack. The Balaena Bay experiment demonstrated that oil spilled under sea ice in the nearshore zone migrates up through brine channels to the surface relatively quickly. The situation offshore, where the brine channel system is poorly developed, has yet to be tested. There are two schools of thought on this: one group feels that oil released under offshore ice, or transported there by the Beaufort Gyre, will not reach the surface for at least four or five years. The other group holds the opinion that the time elapsed would be much shorter. This type of information, crucial for understanding the long-term impact of oil,



▲ Smoke plume from burning crude oil from melt ponds in Balaena Bay, June 1975. Example of how one form of pollution converts into another.

BILL ADAMS

must be assessed. The Balaena Bay controlled spill showed that oil entrained in sea ice is not subject to normal biodegradation and weathering processes.

Unfortunately, an excellent opportunity to study oil biodegradation over the long-term was lost when the experimental oil spill at Balaena Bay was carefully cleaned up after only six months. Continuous chemical and biological monitoring over several years could have provided valuable data on spills in open water as well as under sea ice. Nevertheless, future monitoring of oilspill sites elsewhere in the Arctic may yield useful information on the role of bacterial and weathering processes in the breakdown of oil.

Although many theories and scenarios have been circulated to explain what would happen if oil were released in the plume area of the Mackenzie Delta, information on the rate of sedimentation of oil, the transport of oil-laden sediments, the rate of natural cleansing of sediments, etc., could only be established by *in situ* studies. A slight variation on the Balaena Bay spill could be conducted in waters near the mouth of the Mackenzie River in order to document the effects of the heavy sediment load on the behavior and fate of oil in the estuary.

Given that there is considerable baseline information on the effects of crude oil on organisms of the world's temperate seas, the applicability of these results to the Arctic situation remains suspect. In addition to colder water temperatures there are the added complications (at least in the Beaufort Sea region), of fresh/saltwater, clear/turbid interfaces, and prolonged periods of ice cover and darkness. Before we can hope to understand the long-term impact of oil on the arctic marine environment it will be necessary to assess the sublethal effects of oil on behavior, growth and reproduction of a much larger group of plants and animals. Virtually all this type of information has been generated from laboratory investigations; field corroboration of these results would prove invaluable for future predictions. It will be necessary to bioassay a much larger group of plant, invertebrate and fish species that are native to the area than was possible in the Beaufort Sea Project. As well, toxicity studies should be approached on an ecosystem or community basis rather than being restricted to the single specie's case as has been the norm in past investigations. Seasonal sensitivities of plants and animals to petroleum contamination must also receive closer attention in future research.

Appendix A. Objectives of Beaufort Sea Project Studies Pertinent to this Overview Document.*

1. PHYSICAL/CHEMICAL

a. Baseline Data (12a, 13, 18, 27, 29, 38)

To collect and document existing physical and chemical data in the nearshore and offshore Beaufort Sea.

To gather additional information on surface and subsurface water temperature, salinity and dissolved oxygen.

To determine nutrient levels and their distribution in the water column.

To measure turbidity levels and the penetration of light.

To establish particulate and dissolved organic carbon levels.

To measure physical and chemical parameters of the sediments.

To determine baseline hydrocarbon levels in the water column, sediments, and marine organisms in the Beaufort Sea.

To monitor changes in the physical and chemical parameters of waters subjected to an oil spill in winter.

2. ECOLOGICAL

a. Biodegradation (10).

To determine if a biodegradation potential exists in the Southern Beaufort Sea.

To determine rates of biodegradation at various temperatures and the *in situ* rates.

To ascertain optimum temperature for oil degradation.

To establish the nutrient requirements at optimum and sub-optimum temperatures.

b. Nitrogen-Fixation (9).

To isolate and enumerate the micro-organisms responsible for nitrogen-fixation in Beaufort Sea sediments.

To determine the effect of weathered and unweathered crude oil on the rate of fixation.

To establish the vertical and horizontal distribution of nitrogen fixing activity in Arctic marine sediments.

c. Primary Producers (12a, 12c, 27, 29)

To gather baseline information on the distribution and abundance of marine and estuarine phytoplankton and macrophytes.

To measure chlorophyll levels and the rates of primary production in Beaufort Sea waters.

To establish the importance to primary production of the ice-biota.

To determine the extent to which oil under ice influences photosynthesis and the distribution and abundance of phytoplankton.

d. Zooplankton and Benthos (11, 12b, 27, 29)

To document existing knowledge of the zooplankton and of benthic invertebrates.

To determine the diversity and biomass of the zooplankton and zoobenthos.

To examine the behavioral response of selected invertebrates to crude oil and to oil-tainted food.

To determine the toxic levels of crude oil and oil dispersants on Arctic marine invertebrates.

d. Fish (6, 7, 8)

To gather baseline information on the life history of freshwater, anadromous and marine fishes in the Beaufort Sea area.

To establish areas and times critical to the maintenance of the resources.

To determine migration routes and timing of major fish species.

To define the distribution and abundance of fish species both nearshore and offshore.

To collect and document existing knowledge of oil toxicity.

3. RESOURCE UTILIZATION

a. Fish (6, 7, 8, 32)

To document the historical importance of the fish resources to the local peoples.

To determine present domestic and commercial use of fish in the Beaufort Sea area.

To examine the possible impact of offshore drilling on socio-economics.

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* Bracketed numbers refer to technical reports listed in Appendix B.

Appendix B. Authors and Titles of Beaufort Sea Technical Reports Utilized in the Preparation of this Overview.*

Report No.	Titles and Authors
6.	Fishes of the Yukon Coast - R. Kendel, R. Johnston, U. Lobsiger and M. Kozak.
7.	Fishes Offshore in the Beaufort Sea - J. Hunter and D. Galbraith.
8.	Fishes of the Outer Mackenzie Delta - R. Percy
9.	Nitrogen Fixation in Arctic Marine Sediments - R. Knowles
10.	Biodegradation of Crude Petroleum by the Indigenous Microbial Flora of the Beaufort Sea - J. Bunch and R. Harland.
11.	Effects of Crude Oil on Arctic Marine Invertebrates - J. Percy and T. Mullen.
12a.	Biological Productivity of the Southern Beaufort Sea: the Physical - Chemical Environment and the Plankton - E. Grainger.
12b.	Biological Productivity of the Southern Beaufort Sea: Zoobenthic Studies - J. Wacasey.
12c.	Biological Productivity of the Southern Beaufort Sea: Phytoplankton and Seaweeds - D. Hsiao.
13.	Tar and Particulate Pollutants on the Beaufort Sea Coast - C. Wong, D. MacDonald and W. Cretney.
18.	Physical Oceanography of the Southern Beaufort Sea - R. Herlinveaux and B. de Lange Boom.
27.	The Interaction of Crude Oil with Arctic Sea Ice-Norcor Engineering and Research Limited.
29.	Light Intensity and Primary Productivity Under Sea Ice Containing Oil - W. Adams.
32.	Socio-Economic Importance of Renewable Resource Utilization in the Beaufort Sea - W. Brakel.

38. Hydrocarbon Levels in the Marine Environment of the Southern Beaufort Sea - C.S. Wong, W.J. Cretney, R.W. MacDonald and P. Christensen.

* Only those Beaufort Sea studies that were extensively referred to during the preparation of this overview have been listed. The results of the Beaufort Sea Project are contained in some 46 technical reports.